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The Atlantic Current through the Faroe—Shetland Channel

and its Influence on the Hydrographical Conditions in the Northern Part of the North Sea, the Norwegian Sea, and the Barents Sea.

By

J. P. Jacobsen.

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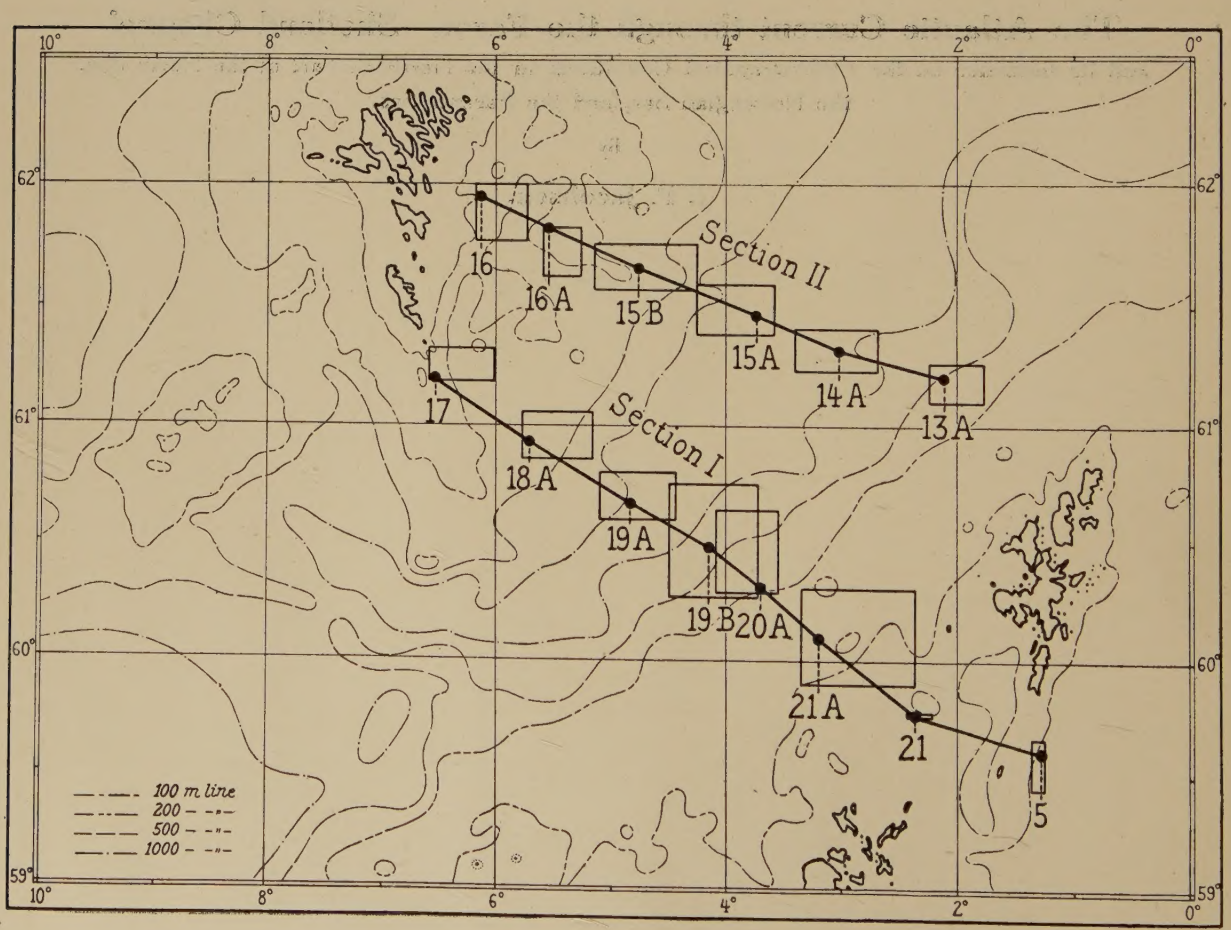


Fig. 1.

A. Introduction.

THE depths of the Faroe—Shetland Channel are shown on the map, Fig. 1. The threshold between the Atlantic and the Norwegian Sea reaches its maximum depth (about 600 m.) at about 60°10′N. and 7°30′W. Between the Faroes and the Shetland Islands the maximum depth of the Channel ranges from about 1100 to 1400 metres.

The area dealt with in the discussion to follow extends from 59°00′ to 62°30′N. and from 0° to 8°W. From 1902 to 1939 numerous observations of temperature and salinity were made at hydrographical stations in this area. Up to 1928 the bulk of the material was collected by Danish, Norwegian and Scottish vessels, since then Dutch, English, French, German and Swedish vessels also have contributed to the collection of data. A general view of the hydrographical stations from which material has been published or is going to be published in the *Bulletin Hydrographique* is given in Tab. 1.

This table shows that investigations have been carried out mainly during the summer months. During the great war, 1914—18, investigations were very scarce and in the years that followed they were not resumed on any large scale until 1922. During the period 1902—14 the hydrographical stations were mostly situated in two sections marked I and II in Fig. 1. From 1922 to 1940 hydrographical investigations were also carried out in these sections but not so regularly as before 1914, investigations in other sections taking the place of some of them. In co-operation between Denmark, Norway and Scotland hydrographical investigations were carried out in May 1924 on a close net of stations.

Among previous papers on investigations within the Faroe—Shetland Channel area the following may be mentioned.

1894. In the XII[th] *Scottish Fishery Board Report* (1893), pt. III, p. 336, H. N. Dickson has treated material collected by the "Jackal" and in the *Geographical Journal* April 1903, p. 422, observations made by Wolfenden are published.

1905. In reports from the North Sea Fish. Invest. Comm. (Fishery Board for Scotland) B. Helland-Hansen has published results of investigations made in 1902.

1907 to 1913. In the series of publications cited above A. J. Robertson has published results of investigations carried out in the Faroe—Shetland Channel and in the northern North Sea in the years 1904 to 1910.

1909. In "The Norwegian Sea" — *Report on Norwegian Fishery and Marine Investigations*, Vol. II, No. 2 — B. Helland-Hansen and F. Nansen on the basis of the material then at disposal have discussed the inflow of Atlantic water through the Faroe—Shetland Channel into the Norwegian Sea and its influence on the hydrographical conditions there.

Table 1.
Number of Stations.

Nation	Depth at the Stations	Jan.	Febr.	March	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Denmark	≤200 m.	9	3	3	22	141	77	56	104	19	3	—	—
	>200 m.	—	—	—	7	77	13	24	15	6	—	—	—
Norway	≤200 m.	—	—	4	37	26	—	6	15	19	—	—	—
	>200 m.	—	—	2	—	25	5	—	46	—	—	1	—
Scotland	≤200 m.	2	25	145	140	191	209	219	217	89	25	96	15
	>200 m.	—	6	4	26	106	81	40	105	17	—	16	6
Other Nations	≤200 m.	—	—	—	—	28	31	25	6	—	—	—	—
	>200 m.	—	—	—	—	1	1	1	4	—	—	—	—

1911. In Medd. fra Komm. for Havundersøgelser, Vol. II, No. 1, Martin Knudsen has published results of investigations carried out in 1910 by the Danish vessel "Thor".

1926. In Rapp. et Proc.-Verb., Vol. XXXIX, p. 31, J. P. Jacobsen and Aage J. C. Jensen have published results of investigations in the Faroe—Shetland Channel from 3/V to 14/V 1924 carried out in co-operation between a Danish, a Norwegian and a Scottish vessel.

1930. In Fisheries, Scotland, Sci. Invest., 1930, No. II and No. IV, John B. Tait has published results of drift-bottle experiments in the northern North Sea and in the Faroe—Shetland Channel.

1934. In Rapp. et Proc.-Verb., Vol. LXXXIX, pt. III, p. 69, John B. Tait has published a paper on "Surface Drift-Bottle Results in Relation to Temperature, Salinity and Density Distributions in the Northern North Sea".

1903—1913. The *Bulletin Hydrographique* contains preliminary treatments of the material from the Faroe—Shetland Channel published in the form of sections with isotherms and isohalines. Material published in the Bulletin after 1913 has not been subjected to such treatment.

Several other publications concerning the flow of Atlantic water through the Faroe—Shetland Channel and its spreading into the Norwegian Sea and adjacent waters will be mentioned later. The present paper has been prepared at the initiative of Professor Martin Knudsen, who has followed the work and given directions as to the lines along which it was to be handled.

Mag. scient. J. Smed has undertaken the numerical calculations and assisted generally. The dynamical calculations and the drawing of the sections are based on the material in the *Bulletin Hydrographique* (see Tab. 1). In the discussion of the spreading of Atlantic water into the Norwegian Sea, on the basis of TS-diagrams, the card index prepared by the Administrative Secretary, Captain W. Nellemose, was used. This card index also covers the majority of observations published in other series than the Bulletin. A collection of TS-diagrams prepared by the former Hydrographical Secretary, cand. A. Lomholt, was used directly as part of the whole collection of such diagrams used in the work.

B. The Normal Distribution of Temperature and Salinity in the Faroe—Shetland Channel.

Columns 1, 2, 6, and 7 of Tab. 4, p. 15, give the years and months of the hydrographical investigations at stations in the two Sections I and II shown in Fig. 1. Material from these investigations has been used in drawing up Tabs. 2a—c and 3a —c, which contain the mean values of temperature and salinity at depths of 0, 50, 100, 200, 300, 400, 500, 600, 800, 1000, and 1200 m. at stations in the above-mentioned sections in the quarters April—May—June, July—August—September, and October—November—December respectively. At the head of each table the medium-date for the investigations is recorded as well as the number of times the section was worked. For each of the stations the following items are recorded under the headings of the table: (1) the name of the station as used in the *Bulletin Hydrographique*, (2) the area just comprising the positions of the stations at different times, and (3) the mean position of the station. The names of the stations, the areas and the mean positions are also shown in Fig. 1.

The figures placed above the tabulated mean values for temperature and salinity indicate the number of observations used in their calculation. In some few cases the values used for the calculation of the means have been interpolated.

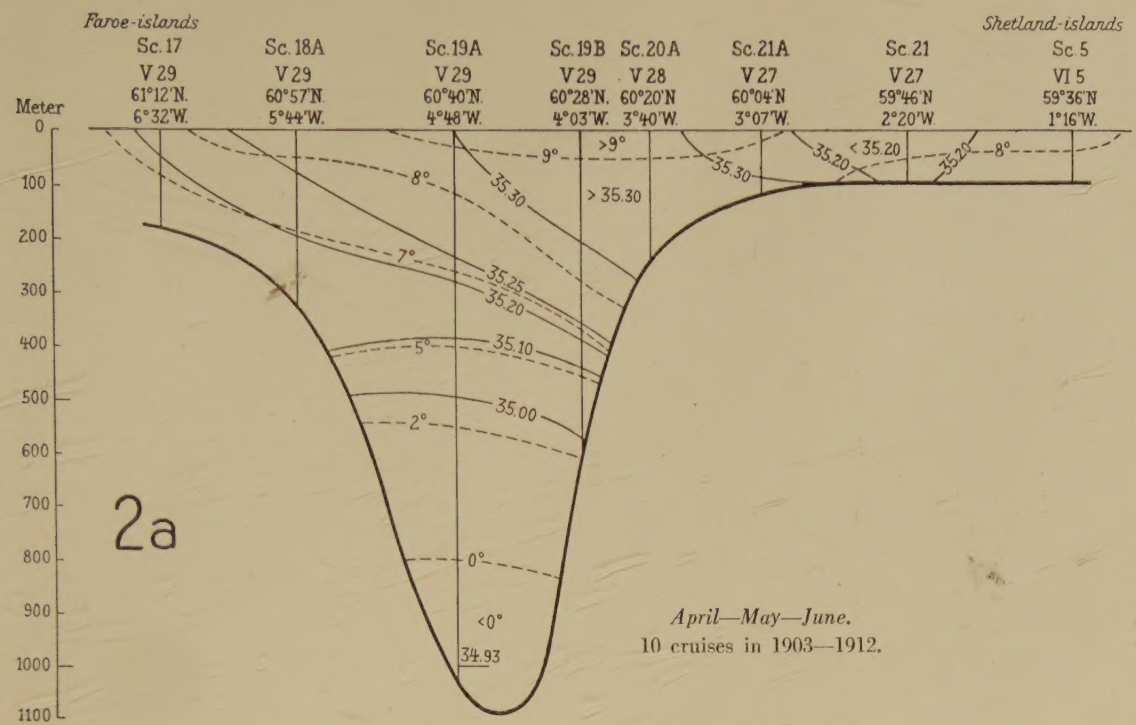
Figs. 2a—c and 3a—c have been drawn on the basis of Tabs. 2a—c and 3a—c with a slight smoothing of the curves, but without any special hypothesis as to their course. From Tabs. 2 and 3 as well as from Figs. 2 and 3 it will be seen that temperature and salinity are highest in the south-eastern part of the sections. This is an indication of the fact that the inflow of Atlantic water into the Norwegian Sea is greatest along the south-eastern side of the channel where the depth is about 500 m. Stations 19B and 13A in Sections I and II are situated in the area with the normally strongest inflow.

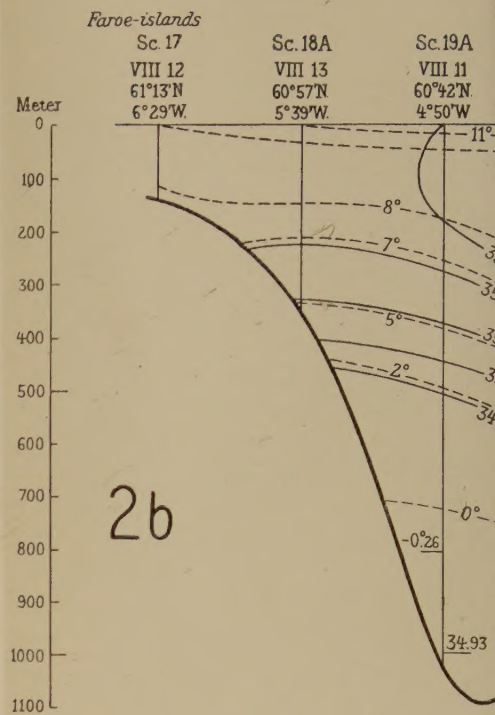
The Atlantic water flowing through the Faroe—Shetland Channel into the Norwegian Sea is strongly mixed with water from areas north of the Faroe—Shetland ridge. In the Faroe—Shetland Channel, down to a depth of 500 m., the water may be regarded as consisting of two components, namely:—

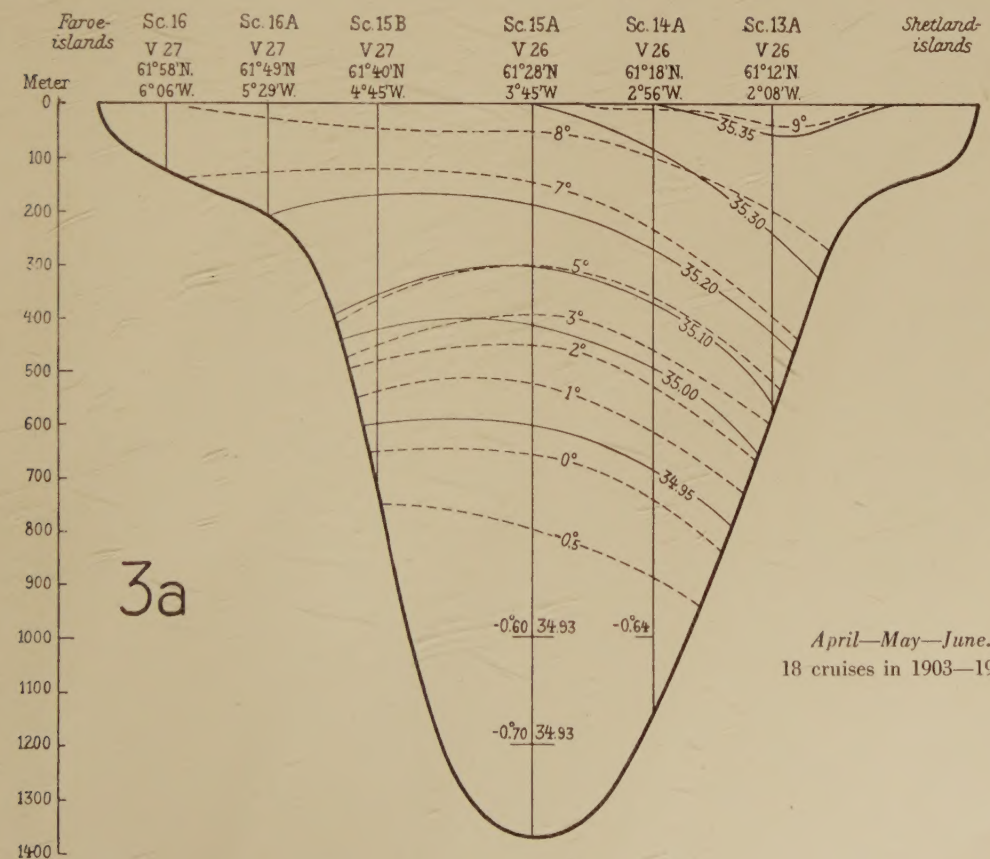
(1) Atlantic water of 10·2° temperature and 35·45 $^0/_{00}$ salinity widely extended in areas west of Ireland down to depths of about 500 m.

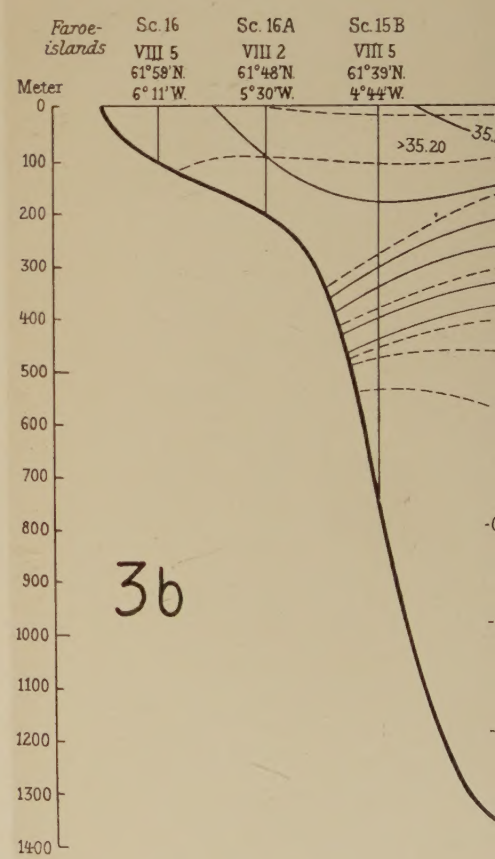
(2) Waters of 2·5° temperature and 34·90 $^0/_{00}$ salinity found north and north-east of Iceland at depths of about 300—400 m. and also largely extended in the Norwegian Sea.

The mean values of temperature and salinity at Stations 19B and 13A, as shown in Tabs. 2a—c and 3a—c have been used for the construction of the TS-diagrams in Figs. 4a—c and 5a—c. The mean positions and the medium-dates of the observations are given above the figures. At the points marked on the TS-curves the depths of the observations are given in hectometres. The dotted straight lines in the diagrams connect points representing

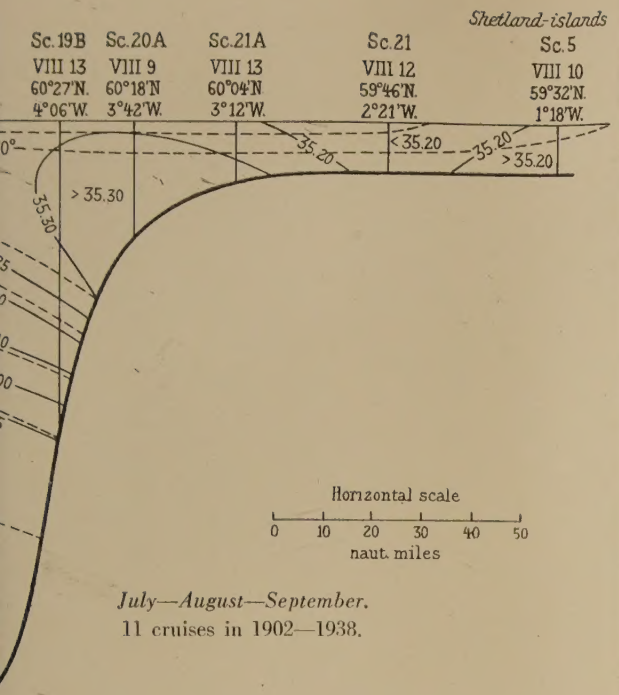




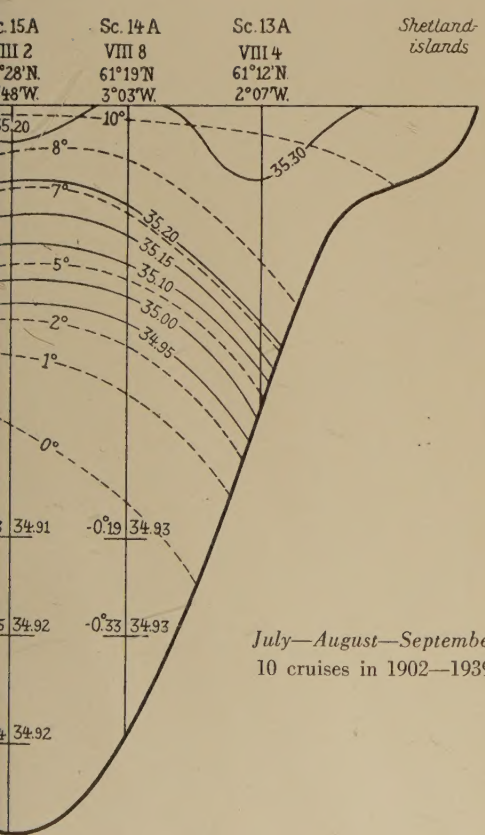




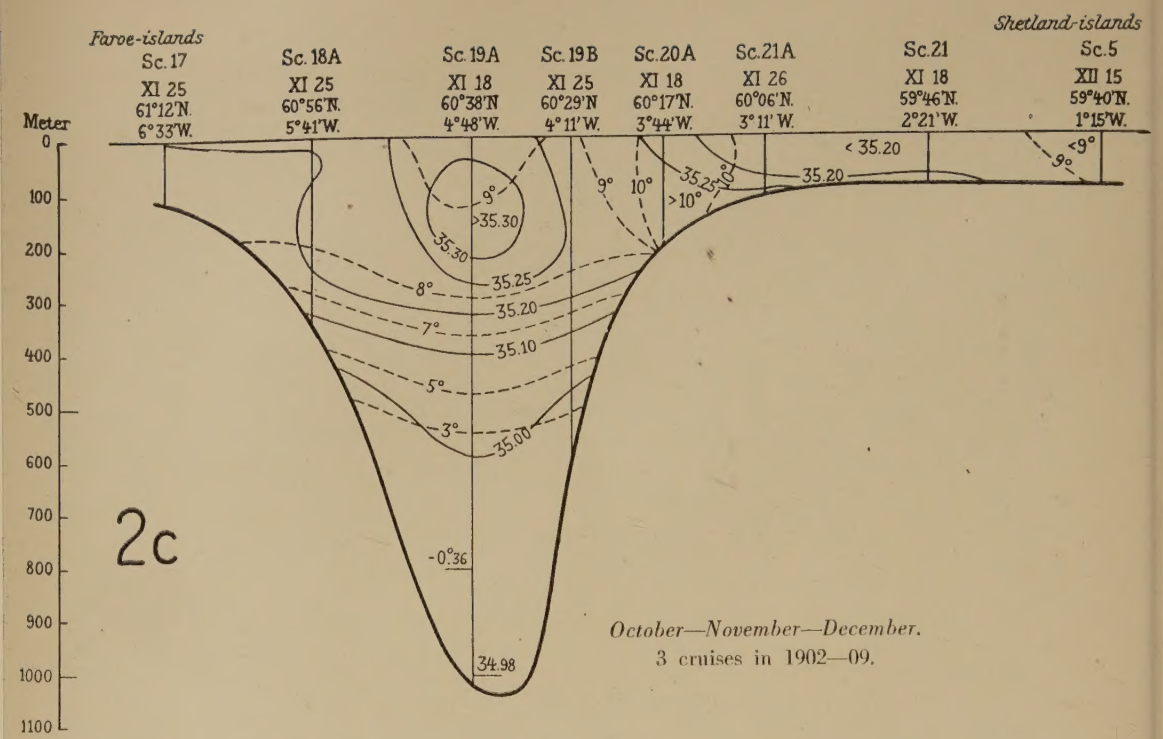
Figs. 2 a—c: Section I; **Figs. 3 a—c:** Section II; drawn on the basis of material from cruises as noted for the individual figures.



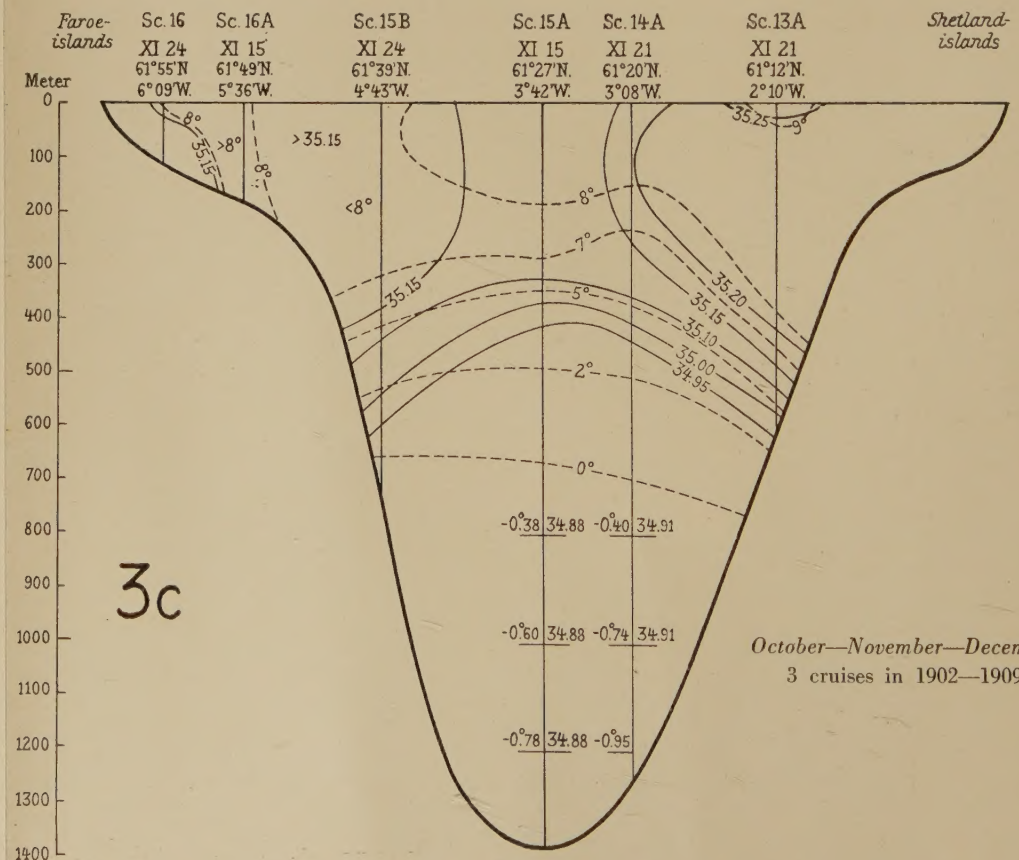
July—August—September.
11 cruises in 1902—1938.



July—August—September.
10 cruises in 1902—1939.



October—November—December.
3 cruises in 1902—09.



October—November—December.
3 cruises in 1902—1909.

Table 2a. Section I. April—May—June.

Medium-date: May 29. The section was worked 10 times 1903—1912.

Depth Metres	Sc 17 61°11′N-61°16′N 6°27′W-6°34′W 61°12′N 6°32′W.		Sc 18A 60°56′N-60°57′N 5°26′W-5°47′W 60°57′N 5°44′W		Sc 19A 60°36′N-60°42′N 4°31′W-5°00′W 60°40′N. 4°48′W		Sc 19B 60°23′N.-60°45′N. 3°50′W.-4°20′W. 60°28′N. 4°03′W.		Sc 20A 60°17′N.-60°38′N 3°33′W.-3°57′W 60°20′N 3°40′W.		Sc 21A 60°02′N.-60°14′N 2°22′W.-3°13′W 60°04′N 3°07′W.		Sc 21 59°46′N.-59°46′N 2°11′W-2°21′W 59°46′N 2°20′W.	
	t	S	*t*	S	*t*	S	*t*	S	*t*	S	*t*	S	*t*	S
0	10 7·68	10 35·23	10 8·87	10 35·28	10 9·18	10 35·30	10 9·61	10 35·34	9 9·63	9 35·35	9 9·11	9 35·21	9 8·67	9 35·14
50	10 7·19	10 35·18	10 7·92	10 35·24	10 8·26	10 35·27	10 9·03	10 35·32	9 8·97	9 35·33	9 8·48	9 35·28	9 7·86	9 35·15
100	10 6·95	10 35·19	10 7·45	10 35·23	10 7·96	10 35·26	10 8·68	10 35·31	9 8·71	9 35·33	8 8·22	8 35·31	1 7·65	1 35·31
200	1 7·27	1 35·17	10 6·97	10 35·20	10 7·47	10 35·23	10 8·39	10 35·30	3 8·42	3 35·33	3 8·11	3 35·32	—	
300	—	—	9 6·40	9 35·19	10 6·54	10 35·18	10 8·05	10 35·29	2 8·06	2 35·30	—			
400	—	—	2 5·79	2 35·14	10 4·99	10 35·07	6 6·62	6 35·19	2 7·46	2 35·24	—			
500	—	—	—	—	10 2·88	10 35·00	3 3·28	3 35·04	1 6·95	1 35·18	—			
600	—	—	—	—	10 1·51	10 34·95	3 2·08	3 35·01	—	—	—			
800	—	—	—	—	10 –0·11	10 34·93	1 –0·91	1 34·96	—	—	—			
1000	—	—	—	—	8 –0·69	8 34·93	—	—	—	—	—			

Depth Metres	Sc 5 59°26′N.-59°40′N. 1°14′W.-1°20′W. 59°36′N. 1°16′W.	
	t	S
0	4 8·63	4 35·28
50	4 7·72	4 35·28
100	1 7·37	1 35·37

Table 2b. Section I. July—August—September.

Medium-date: August 12. The section was worked 11 times 1902—38.

Depth Metres	Sc 17 61°11′N.-61°19′N 6°00′W -6°34′W 61°13′N 6°29′W		Sc 18A 60°52′N.-61°03′N. 5°08′W.-5°47′W. 60°57′N 5° 39′W		Sc 19A 60°36′N.-60°48′N. 4°25′W.-5°03′W. 60°42′N. 4°50′W		Sc 19B 60°16′N.-60°38′N. 3°45′W.-4°29′W. 60°27′N 4°06′W.		Sc 20A 60°17′N.-60°22′N. 3°36′W.-4°04′W. 60°18′N 3°42′W.		Sc 21A 59°54′N.-60°18′N. 2°53′W.-3°21′W. 60°04′N 3°12′W.		Sc 21 59°46′N.-59°47′N. 2°21′W.-2°25′W. 59°46′N 2°21′W.	
	t	S	*t*	S	*t*	S	*t*	S	*t*	S	*t*	S	*t*	S
0	11 10·02	11 35·20	11 11·23	11 35·22	10 11·77	10 35·25	11 11·84	11 35·28	8 11·92	8 35·29	11 12·10	11 35·21	9 11·49	9 35·12
50	11 8·88	11 35·20	11 9·40	11 35·24	10 9·62	10 35·26	11 10·24	11 35·31	8 10·38	8 35·34	11 10·53	11 35·26	9 10·18	9 35·16
100	11 8·42	11 35·21	11 8·21	11 35·26	10 8·48	10 35·27	11 9·12	11 35·32	6 9·38	8 35·35	9 9·47	9 35·34	1 9·44	1 35·17
200	2 8·08	2 35·28	11 7·46	11 35·22	10 7·65	10 35·24	11 8·65	11 35·31	4 9·24	4 35·37	—			
300	—	—	10 6·44	10 35·17	10 6·35	10 35·17	9 7·74	9 35·25	2 8·94	2 35·31	—			
400	—	—	4 3·55	4 35·00	10 4·23	10 35·05	9 6·78	9 35·23	1 7·70	1 35·25	—			
500	—	—	1 –0·04	1 34·91	10 2·05	10 34·95	6 4·44	6 35·06	—	—	—			
600	—	—	1 –0·59	1 34·91	10 0·47	10 34·94	2 2·28	2 34·95	—	—	—			
800	—	—	—	—	9 –0·26	9 34·94	1 –0·23	1 34·93	—	—	—			
1000	—	—	—	—	7 –0·46	7 34·93	1 –1·16	1 34·93	—	—	—			

Depth Metres	Sc 5 59°26′N.-59°40′N. 1°14′W.-1°20′W. 59°32′N. 1°18′W.	
	t	S
0	5 10·71	5 35·22
50	5 9·71	5 35·23
100	3 8·54	3 35·24

Table 2c. Section I. October—N o v e m b e r—December.
Medium-date: November 25. The section was worked 3 times 1902—1909.

Depth Metres	Sc 17 61°11′N.-61°13′N. 6°33′W.-6°34′W. 61°12′N. 6°33′W.		Sc 18A 60°53′N.-60°57′N. 5°30′W.-5°47′W. 60°56′N. 5°41′W.		Sc 19A 60°36′N.-60°40′N. 4°46′W.-4°50′W. 60°38′N. 4°48′W.		Sc 19B 60°25′N.-60°35′N. 4°02′W.-4°26′W. 60°29′N. 4°11′W.		Sc 20A 60°17′N.-60°17′N. 3°36′W.-3°52′W. 60°17′N. 3°44′W.		Sc 21A 60°02′N.-60°13′N. 3°09′W.-3°13′W. 60°06′N. 3°11′W.		Sc 21 59°46′N.-59°46′N. 2°21′W.-2°21′W. 59°46′N. 2°21′W.		Sc 5 59°40′N.-59°40′N. 1°15 W--1°15′W. 59°40′N. 1°15′W.	
	t	S	*t*	S	*t*	S	*t*	S	*t*	S	*t*	S	*t*	S	*t*	S
0	8·19 (3)	35·21 (3)	8·44 (3)	35·21 (3)	9·34 (2)	35·28 (2)	8·64 (3)	35·24 (3)	10·26 (2)	35·23 (2)	9·76 (3)	35·16 (3)	9·54 (2)	35·10 (2)	7·95 (1)	33·86 (1)
50	8·55 (3)	35·17 (3)	8·42 (3)	35·19 (3)	9·29 (2)	35·29 (2)	8·98 (3)	35·22 (3)	10·35 (2)	35·24 (2)	9·94 (3)	35·17 (3)	9·52 (2)	35·19 (2)	8·46 (1)	35·09 (1)
100	8·38 (2)	35·18 (2)	8·27 (3)	35·21 (3)	9·12 (2)	35·33 (2)	8·55 (3)	35·22 (3)	10·30 (2)	35·30 (2)	9·62 (2)	35·25 (2)	9·91 (1)	35·24 (1)	8·56 (1)	35·08 (1)
200	—	—	7·97 (3)	35·21 (3)	8·60 (2)	35·31 (2)	8·48 (3)	35·26 (3)	10·10 (2)	35·30 (2)	—	—	—	—	—	—
300	—	—	7·56 (2)	35·18 (2)	7·84 (2)	35·24 (2)	7·29 (3)	35·20 (3)	—	—	—	—	—	—	—	—
400	—	—	6·93 (1)	35·13 (1)	6·21 (2)	35·09 (2)	5·64 (3)	35·16 (3)	—	—	—	—	—	—	—	—
500	—	—	1·63 (1)	34·94 (1)	4·55 (2)	35·06 (2)	2·46 (2)	34·98 (2)	—	—	—	—	—	—	—	—
600	—	—	1·74 (1)	34·92 (1)	1·84 (2)	34·96 (2)	—	—	—	—	—	—	—	—	—	—
800	—	—	—	—	–0·36 (2)	34·98 (2)	—	—	—	—	—	—	—	—	—	—
1000	—	—	—	—	–0·73 (2)	34·98 (2)	—	—	—	—	—	—	—	—	—	—

Table 3a. Section II. April—M a y—June.
Medium-date: May 26. The section was worked 18 times 1903—1938.

Depth Metres	Sc 16 61°46′N.-62°00′N. 5°45′W.-6°12′W. 61°58′N. 6°06′W.		Sc 16A 61°41′N.-61°49′N. 5°17′W.-5°36′W. 61°49′N. 5°29′W.		Sc 15B 61°34′N.-61°42′N. 4°16′W.-5°09′W. 61°40′N. 4°45′W.		Sc 15A 61°23′N.-61°35′N. 3°35′W.-4°15′W. 61°28′N. 3°45′W.		Sc 14A 61°14′N.-61°21′N. 2°40′W.-3°10′W. 61°18′N. 2°56′W.		Sc 13A 61°08′N.-61°16′N. 1°46′W.-2°14′W. 61°12′N. 2°08′W.	
	t	S	*t*	S	*t*	S	*t*	S	*t*	S	*t*	S
0	7·84 (18)	35·23 (18)	8·29 (17)	35·23 (17)	8·43 (18)	35·25 (18)	8·85 (17)	35·30 (17)	9·22 (17)	35·33 (17)	9·50 (18)	35·36 (18)
50	7·35 (18)	35·22 (18)	7·66 (17)	35·22 (17)	7·78 (18)	35·24 (18)	7·96 (17)	35·27 (17)	8·44 (17)	35·31 (17)	8·88 (18)	35·36 (18)
100	7·13 (15)	35·21 (15)	7·07 (17)	35·21 (17)	7·42 (18)	35·23 (18)	7·26 (17)	35·24 (17)	8·02 (17)	35·29 (17)	8·47 (18)	35·33 (18)
200	7·41 (3)	35·30 (3)	6·77 (3)	35·20 (3)	7·10 (17)	35·22 (17)	6·28 (17)	35·19 (17)	7·34 (17)	35·25 (17)	8·03 (18)	35·30 (18)
300	7·52 (1)	35·31 (1)	—	—	5·94 (10)	35·12 (10)	4·99 (17)	35·10 (17)	6·14 (17)	35·18 (17)	7·67 (17)	35·28 (17)
400	—	—	—	—	4·47 (7)	35·05 (7)	3·25 (17)	35·01 (17)	4·43 (17)	35·07 (17)	6·99 (16)	35·23 (16)
500	—	—	—	—	1·65 (4)	34·94 (4)	1·20 (17)	34·96 (17)	2·51 (17)	35·00 (17)	5·28 (13)	35·14 (13)
600	—	—	—	—	0·34 (3)	34·92 (3)	0·27 (17)	34·95 (17)	0·92 (17)	34·95 (17)	2·76 (4)	35·09 (4)
800	—	—	—	—	–0·54 (1)	34·96 (1)	–0·48 (16)	34·93 (16)	–0·32 (17)	34·96 (17)	—	—
1000	—	—	—	—	–0·72 (1)	34·96 (1)	–0·60 (16)	34·93 (16)	–0·64 (16)	34·94 (15)	—	—
1200	—	—	—	—	—	—	–0·70 (12)	34·93 (12)	–0·79 (10)	34·94 (9)	—	—

Table 3b. Section II. July—A u g u s t—September.
Medium-date: August 4. The section was worked 10 times 1902—1939.

Depth Metres	Sc 16 61°47′N.-62°00′N. 6°04′W.-6°12′W. 61°59′N. 6°11′W.		Sc 16A 61°37′N.-61°49′N. 5°18′W.-5°36′W. 61°48′N. 5°30′W.		Sc 15B 61°35′N.-61°45′N. 4°23′W.-5°05′W. 61°39′N. 4°44′W.		Sc 15A 61°26′N.-61°35′N. 3°42′W.-4°15′W. 61°28′N. 3°48′W.		Sc 14A 61°18′N.-61°25′N. 2°50′W.-3°24′W. 61°19′N. 3°03′W.		Sc 13A 61°06′N.-61°16′N. 2°00′W.-2°14′W. 61°12′N. 2°07′W.	
	t	S	*t*	S	*t*	S	*t*	S	*t*	S	*t*	S
0	10 9·56	10 35·19	9 10·32	9 35·21	10 10·16	10 35·20	9 10·47	9 35·17	9 11·12	9 35·20	10 11·50	10 35·31
50	10 8·85	10 35·18	9 9·16	9 35·21	10 8·83	10 35·22	9 8·73	9 35·18	9 8·82	9 35·21	10 9·85	10 35·30
100	10 8·71	10 35·18	9 7·92	9 35·22	10 7·94	10 35·23	9 7·50	9 35·18	9 7·91	9 35·22	9 9·02	10 35·31
200	—	—	5 7·53	5 35·20	10 7·53	10 35·22	9 6·68	9 35·15	9 7·14	9 35·18	9 8·43	10 35·29
300	—	—	—	—	5 6·76	5 35·16	9 4·84	9 35·05	9 5·56	9 35·09	9 7·93	10 35·26
400	—	—	—	—	4 4·50	4 35·00	9 2·23	9 34·93	9 3·23	9 34·95	9 7·14	9 35·20
500	—	—	—	—	2 0·39	2 34·90	9 0·69	9 34·91	9 1·25	9 34·94	8 5·82	8 35·12
600	—	—	—	—	2 –0·39	2 34·94	9 0·04	9 34·91	9 0·49	9 34·94	4 3·02	4 35·02
800	—	—	—	—	—	—	9 –0·53	9 34·91	9 –0·19	9 34·93	1 1·77	1 35·02
1000	—	—	—	—	—	—	9 –0·75	9 34·92	9 –0·33	9 34·93	—	—
1200	—	—	—	—	—	—	5 –0·94	5 34·92	3 –0·88	3 34·92	—	—

Table 3c. Section II. October—N o v e m b e r—December.
Medium-date: November 20. The section was worked 3 times 1902—1909.

Depth Metres	Sc 16 61°44′N.-62°00′N. 6°03′W.-6°12′W. 61°55′N. 6°09′W.		Sc 16A 61°49′N.-61°49 N. 5°36′W.-5°36′W. 61°49′N. 5°36′W.		Sc 15B 61°38′N.-61°39′N. 4°39′W.-4°45′W. 61°39′N. 4°43′W.		Sc 15A 61°27′N.-61°27′N. 3°42′W.-3°42′W. 61°27′N. 3°42′W.		Sc 14A 61°18′N.-61°23′N. 2°59′W.-3°25′W. 61°20′N. 3°08′W.		Sc 13A 61°09′N.-61°16′N. 2°08′W.-2°14′W. 61°12′N. 2°10′W.	
	t	S	*t*	S	*t*	S	*t*	S	*t*	S	*t*	S
0	3 8·02	3 35·16	2 8·16	2 35·18	3 7·69	3 35·18	2 8·22	2 35·10	3 8·45	3 35·17	3 9·22	3 35·30
50	3 7·76	3 35·14	2 8·39	2 35·18	3 7·89	3 35·15	2 8·31	2 35·02	3 8·65	3 35·15	3 9·05	3 35·23
100	3 7·78	3 35·14	2 8·35	2 35·19	3 7·91	3 35·15	2 8·44	2 35·14	3 8·35	3 35·22	3 8·94	3 35·23
200	—	—	1 8·73	1 35·19	3 7·62	3 35·16	2 7·98	2 35·13	3 7·43	3 35·18	3 8·55	3 35·23
300	—	—	—	—	3 7·22	3 35·18	2 7·08	2 35·12	3 5·82	3 35·07	3 8·39	3 35·22
400	—	—	—	—	2 4·60	2 35·06	2 4·80	2 34·95	3 4·55	3 35·06	3 8·07	3 35·23
500	—	—	—	—	2 2·62	2 35·04	2 1·76	2 34·91	3 2·02	3 34·92	2 6·94	2 35·16
600	—	—	—	—	1 0·40	1 34·93	2 0·44	2 34·88	3 0·69	3 34·92	—	—
800	—	—	—	—	1 –0·48	1 34·92	2 –0·38	2 34·88	3 –0·40	3 34·91	—	—
1000	—	—	—	—	—	—	2 –0·60	2 34·88	3 –0·74	3 34·91	—	—
1200	—	—	—	—	—	—	2 –0·78	2 34·88	2 –0·95	2 34·92	—	—

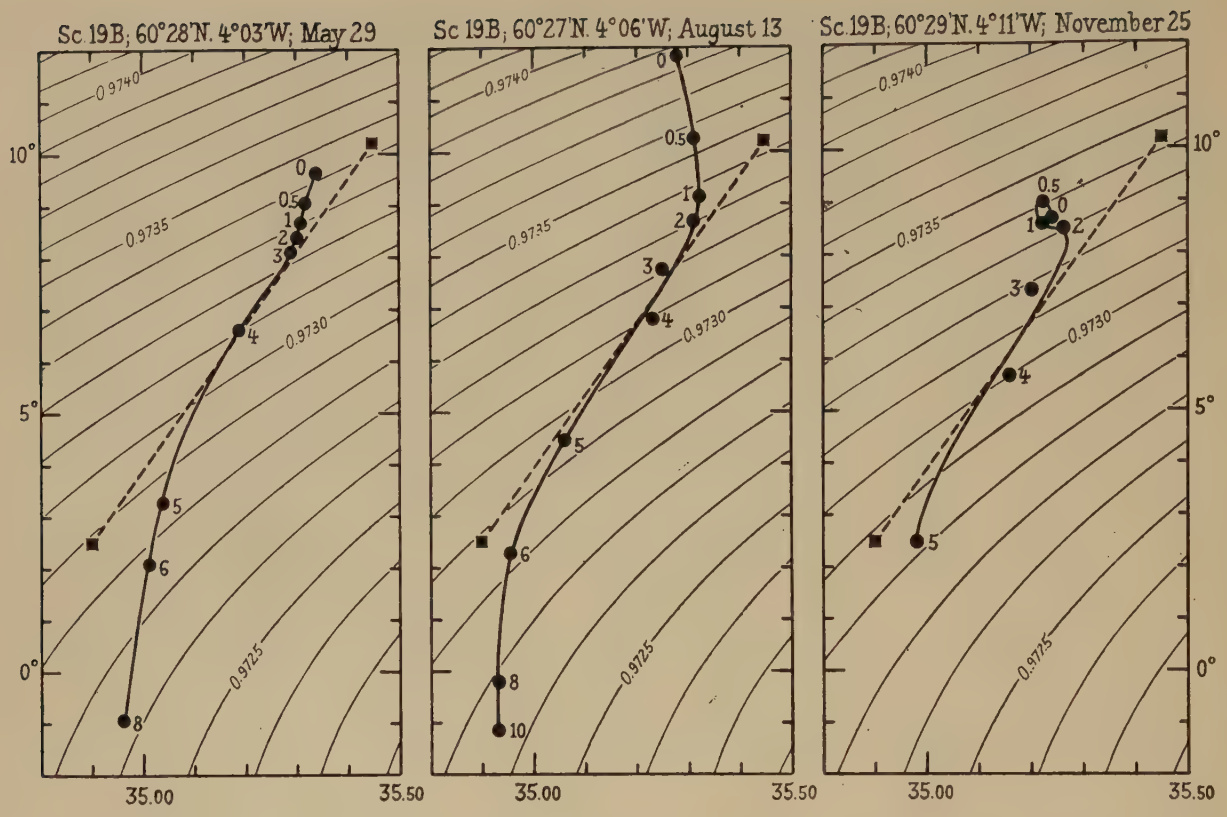


Fig. 4. a. b. c.

the above-mentioned water components with temperatures and salinities of 10·2°, 35·45 ‰, and 2·5°, 34·90 ‰ respectively. Isosteres have been drawn in the diagrams corresponding to a pressure of one atmosphere. The situation of the TS-curves in relation to the isosteres shows the stability of the water layers.

The mixed water indicated by the TS-curves is probably formed in the central part of the Faroe—Shetland Channel, where the depth of the sea is great. In Figs. 4a and 5a representing the conditions in early summer the TS-curves follow the dotted straight lines rather closely to a depth of 400 or 500 m. This is quite in accordance with the fact that the mixed water down to that depth consists of the above-mentioned two components. In Figs. 4b and 5b representing the conditions in summer the TS-curves from the surface down to a depth of about 100 m. deviate considerably from the dotted straight lines. This is caused by a heating from the atmosphere and by the radiation from the sun. The heating of the Atlantic water has undoubtedly taken place before the mixing. The stability of the upper layers of the water is increased by this heating, but nevertheless the mixed water at Station 13A down to 400 m. is of a somewhat higher temperature than that of the water that might be formed by mixing of the two components without heating. Figs. 4c and 5c represent conditions in November, but the figures have been drawn on the basis of three series of observations only from Stations 19B and 13A. Especially the TS-curve for Station 13A shows that in November the upper layers come much nearer to being homogeneous than in spring and summer. This is naturally explained by the fact that cooling in autumn lowers the stability, so that for that reason alone mixing must increase. Weather conditions in autumn will also favour the mixing.

The yearly course of the temperature of the water in the Faroe—Shetland Channel is shown in Figs. 6 and 7 in which are plotted the monthly mean values of the temperature at the depths 0, 50, 100, 200, 300, 400, and 500 m. for Stations 19B and 13A. The solid curves in Figs. 6a and 7a are constructed on the basis of the maps published by C. Ryder[1]), while the dotted curves show the yearly course of the air temperature at Thorshavn (Faroe Islands) according to A. Kiilerich[2]).

[1]) C. Ryder. Monthly mean Temperatures of the Surface water in the Atlantic north of 50° N. Lat. Nautical Meteorological Annual of the Danish Meteorological Institute, 1917.

[2]) A. Kiilerich. Geography, Hydrography and Climate of the Faroes. Zoology of the Faroes, Copenhagen, 1928.

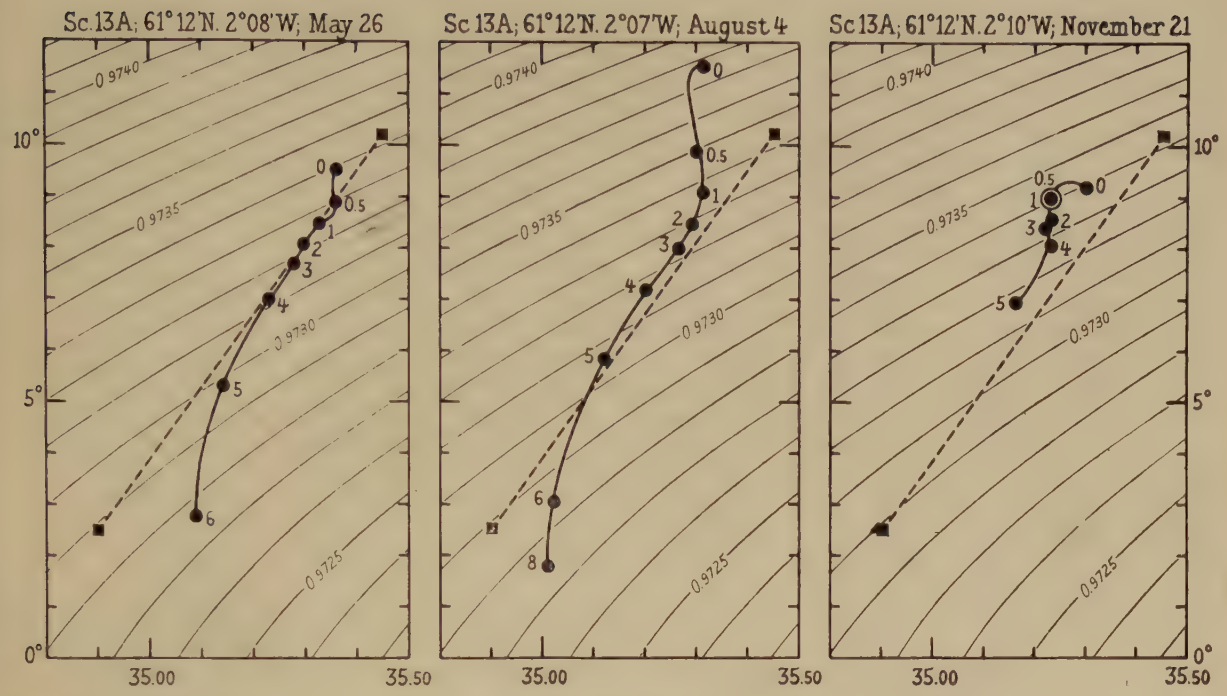


Fig. 5. a. b. c.

The solid curves in Figs. 6b—g and 7b—g have been constructed to represent with some approximation the yearly course of the temperature at the depths in question.

The minimum surface temperature of the year may be estimated to be the same at Stations 19B and 13A, namely about 7·2°, and to occur simultaneously, namely, in February. Down to a depth of about 400 m. the minimum temperature and the time of its occurrence are probably the same as at the surface. On account of the winter-cooling the value 7·2° for the minimum temperature is undoubtedly somewhat lower than that which would arise by a mixing of the components $t = 10{\cdot}2°$, $S = 35{\cdot}45\ ‰$ and $t = 2{\cdot}5°$, $S = 34{\cdot}90\ ‰$ in a ratio given by the salinity of the water in question.

C. Currents in the Faroe—Shetland Channel.

The meeting of Atlantic water and water from the Norwegian Sea causes solenoidal fields to appear in the Faroe—Shetland Channel. The shape of these fields may be determined when the distribution of temperature and salinity is known; and subject to the usual assumption of frictionless stationary water movement with a known zero surface, the water movement in accordance with a solenoidal field may be calculated. The results obtained by such calculations must, however, show some disagreement with the actual movement of the water. Wind and tide must have some influence on the distribution of temperature and salinity, and the relevant changes in a solenoidal field must take place so quickly that observations in a section — as ordinarily performed — cannot be regarded as simultaneous. Further, the number of stations in the cases considered is insufficient to give an exact picture of the distribution of temperature and salinity. Thus the supposed stationary conditions may be but roughly fulfilled. At the choice of the position of the zero-surface, i.e., the surface where the horizontal gradient of the pressure equals zero, some uncertainty also is introduced. Actually the zero-surface may change its place from time to time.

For the material in question the current, given in cm./sec., and the intensity of the flow, given in km.^{3}/hour, were calculated for the different intervals of depths between the different stations. The zero-surface for an interval of two stations was at first supposed to coincide with the isobaric surface at — or near — the bottom at the station with the smallest depth. Later the intensity of the flow was determined on the supposition that a surface consisting of the isobaric surface at the depth of 800 m. and the bottom of the sea for depths less than 800 m. could be taken as zero-surfaces for the sections in question. As to the method of calculation, see Chapter **F.**

In the years 1902—1939 Section I (see Fig. 1.)

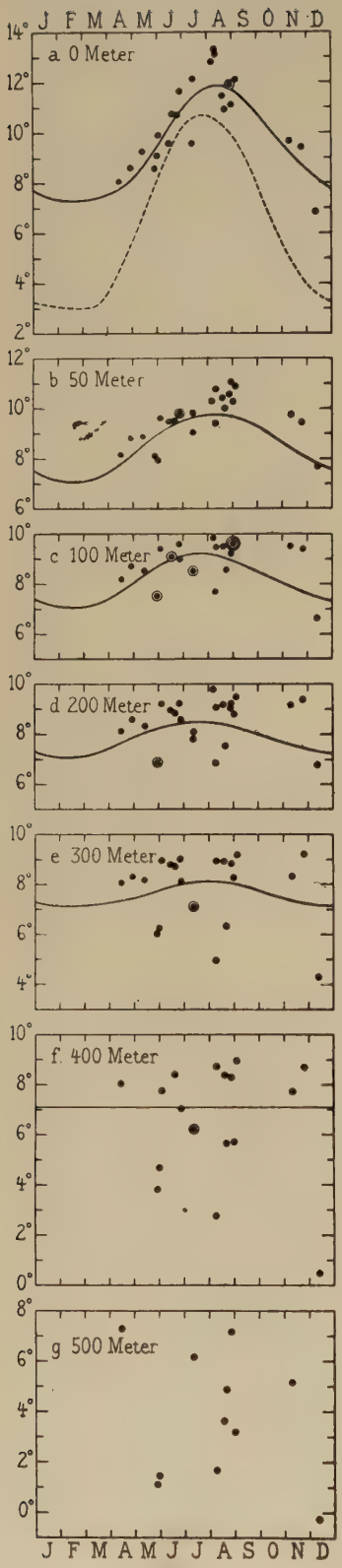


Fig. 6.
Station Sc 19 B.

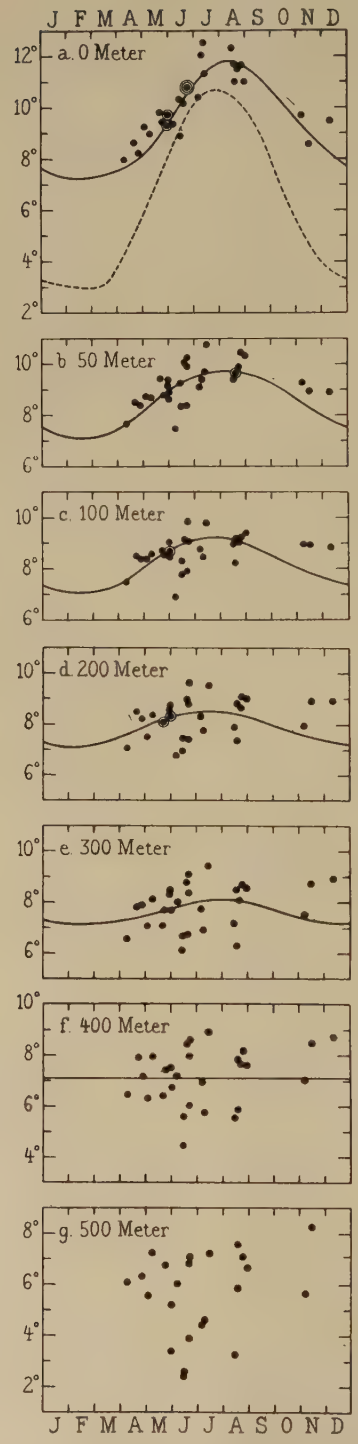


Fig. 7.
Station Sc 13 A.

Monthly Means of Temperature at different depths at Stations Sc 19 B and Sc 13 A (see Fig. 1). The dotted curve in the upper part of the figures represents the air temperature at Thorshavn (Faroe Islands).

Table 4.

Intensity of Total Flow in north-easterly direction through Sections I and II (see Fig. 1).

Section I					Section II				
Year	Month	Dates of observation for stations where the depth was greater than 200m.	Intensity of total flow (km.³/hour) uncorr.	corr.	Year	Month	Dates of observation for stations where the depth was greater than 200m.	Intensity of total flow (km.³/hour) uncorr.	corr.
1902	Aug.	30. 31	2·4	1·4	1902	Aug.	29. 30	23·6	13·0
„	Dec.	11	—10·0	—8·2	„	Dec.	10. 11	12·3	24·4
1903	May—June	31	4·3	12·6	1903	May	29. 30	7·3	12·7
„	Aug.	20. 21	—1·5	8·9	„	Aug.	18	4·9	2·4
1904	May	27. 28	—10·6	6·6	1904	May	30	23·5	21·6
„	Aug.	25. 26	7·2	8·8	„	Aug.	22. 23	2·4	16·7
1905	June	26	4·4	12·8	1905	June	22. 23	13·5	15·8
1906	June	18. 19	6·2	18·5	1906	June	14. 15	2·1	6·1
„	Aug.	28	1·0	13·0	„	Aug.	24. 25	44·0	45·4
1907	July	10. 11	4·9	14·6	1907	July	6. 7	5·1	9·5
1908	April	13. 14	13·6	21·6	1908	April	9. 10	0·0	2·9
„	June	13. 14	5·3	16·5	„	June	7. 9	6·0	18·6
„	Nov.	9. 10	8·5	16·0	„	Aug.	19. 20. 21	16·6	31·3
1909	April	28	2·4	8·2	„	Nov.	7	—1·8	—2·3
„	June	24. 25	4·9	7·6	1909	April	26. 27	—7·2	1·4
„	Aug.	18. 21	10·7	12·4	„	June	20. 21	—2·6	0·9
„	Nov.	24. 25	1·1	4·7	„	Nov.	15. 23	8·6	20·2
1910	Aug.	9	5·4	15·5	1910	May	24. 25	28·9	20·4
1911	May	12. 13	1·8	8·8	„	Aug.	13. 14. 15	3·0	4·9
1912	June	1. 2	5·2	12·4	1911	May	9. 10	19·1	18·9
1913	July	12. 13	0·1	0·0	1912	May	30. 31	8·0	—3·9
1927	Aug.	7. 8	—0·1	9·7	1913	July	9. 10	12·5	9·2
1933	Sept.	1. 2	10·6	24·5	1929	June	22. 23	—7·8	—4·4
1938	Aug.	4. 5	—0·5	1·0	1934	April	21. 22	2·0	9·6
—	—	—	—	—	„	May—June	31. 1	19·0	17·5
—	—	—	—	—	„	July	12	10·7	11·0
—	—	—	—	—	1935	June	18. 19	4·4	10·5
—	—	—	—	—	1936	June	13. 14	—4·3	—0·8
—	—	—	—	—	1937	May	21. 22	1·0	—0·5
—	—	—	—	—	1938	May	3. 4	10·7	9·7
—	—	—	—	—	1939	July	14	9·4	19·4
Mean value			3·2	10·3	Mean value			8·9	11·7
Standard deviation			1·2	1·5	Standard deviation			2·0	2·0

was investigated 24 times and Section II 31 times. Tab. 4 above records the time of the investigations in Columns 1, 2, 3, 6, 7, and 8. Diagrams showing the current and the intensity of the flow through the different parts of the sections have been constructed. Figs. 8, 9 and 10 are examples of such diagrams. The values of the velocity of the current — at right angles to the section and taken as positive when it has a northerly direction — are stated in the diagrams for the different intervals of depth between the stations. These values are found according to the supposition that the zero-surface for an interval between two stations be situated as indicated by the bottom-line of the interval in the diagram. Below the bottom line for each of the intervals of the stations two values are stated for the intensity of the flow through the interval. The upper value is in accordance with the stated values of the current between the stations, the lower corrected value was found by the method mentioned in Chapter **F** in connection with expressions (23) and (32), and thus represents the intensity of the flow in accordance with a supposed zero-surface at a depth of 800 m., or at the bottom of the sea where the depth is less than 800 m. The uncorrected and corrected values of the intensity of the total flow through the section, are recorded at the foot of the diagrams.

Actually, the diagrams in Figs. 8, 9 and 10 show the approximately normal conditions as to water movements in the Faroe—Shetland Channel, with a strong north-going movement of the water in the

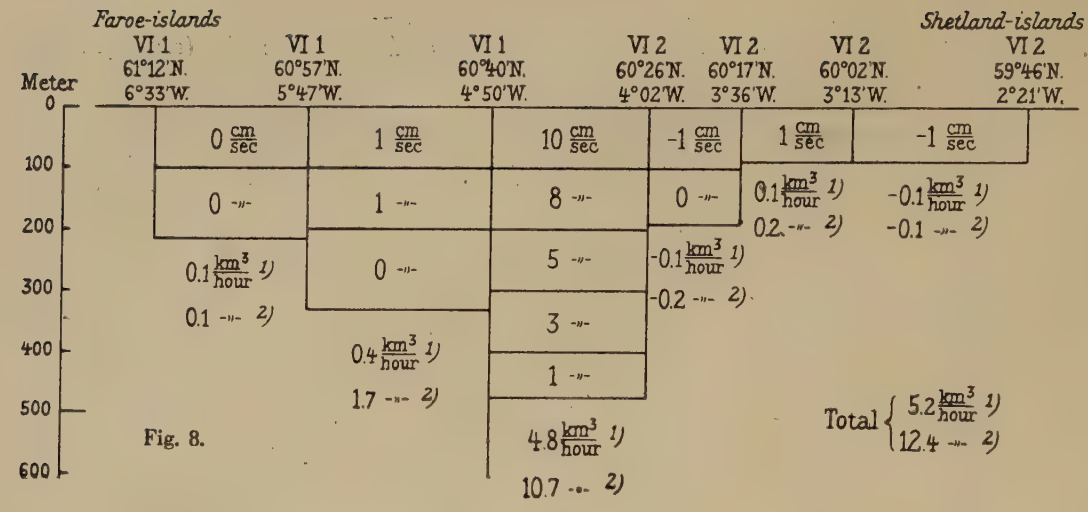
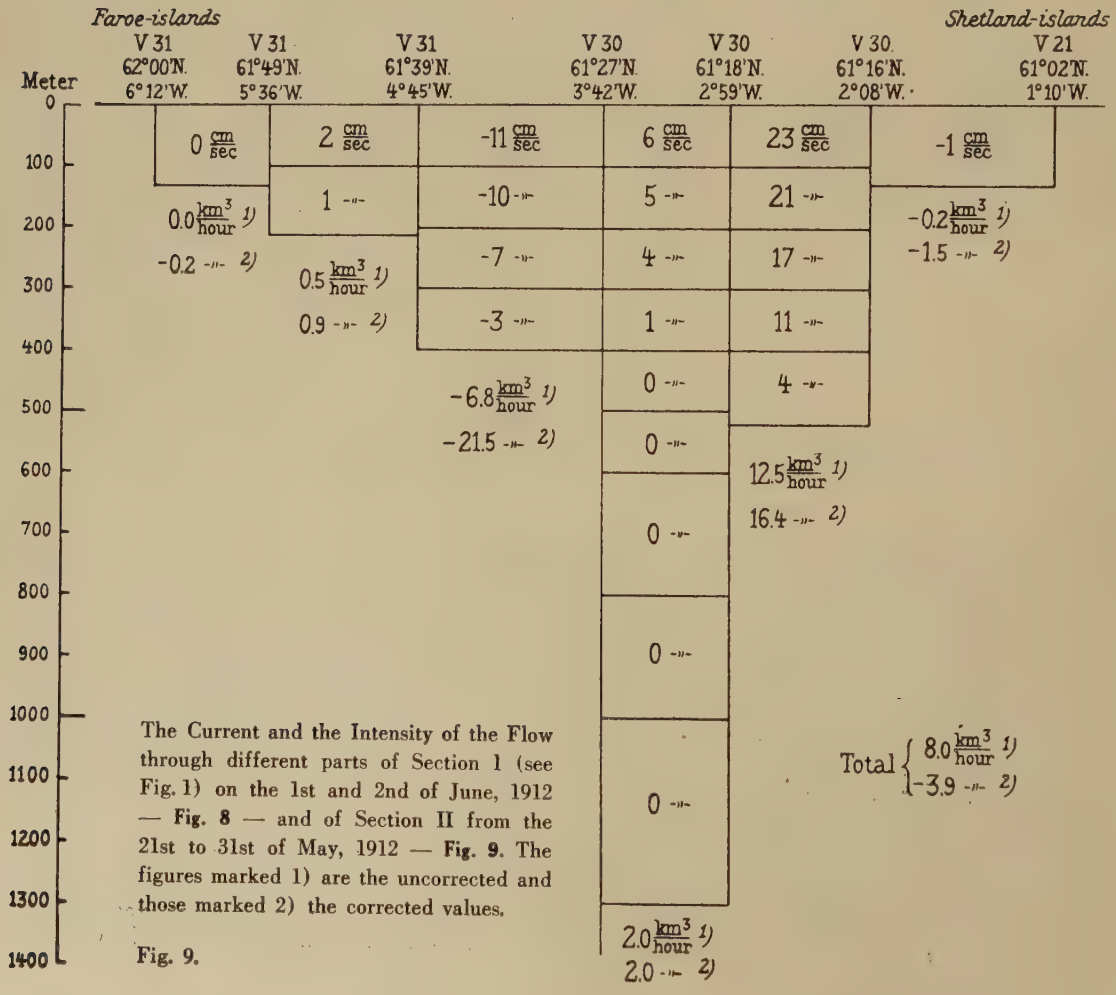


Fig. 8.



The Current and the Intensity of the Flow through different parts of Section I (see Fig. 1) on the 1st and 2nd of June, 1912 — **Fig. 8** — and of Section II from the 21st to 31st of May, 1912 — **Fig. 9**. The figures marked 1) are the uncorrected and those marked 2) the corrected values.

Fig. 9.

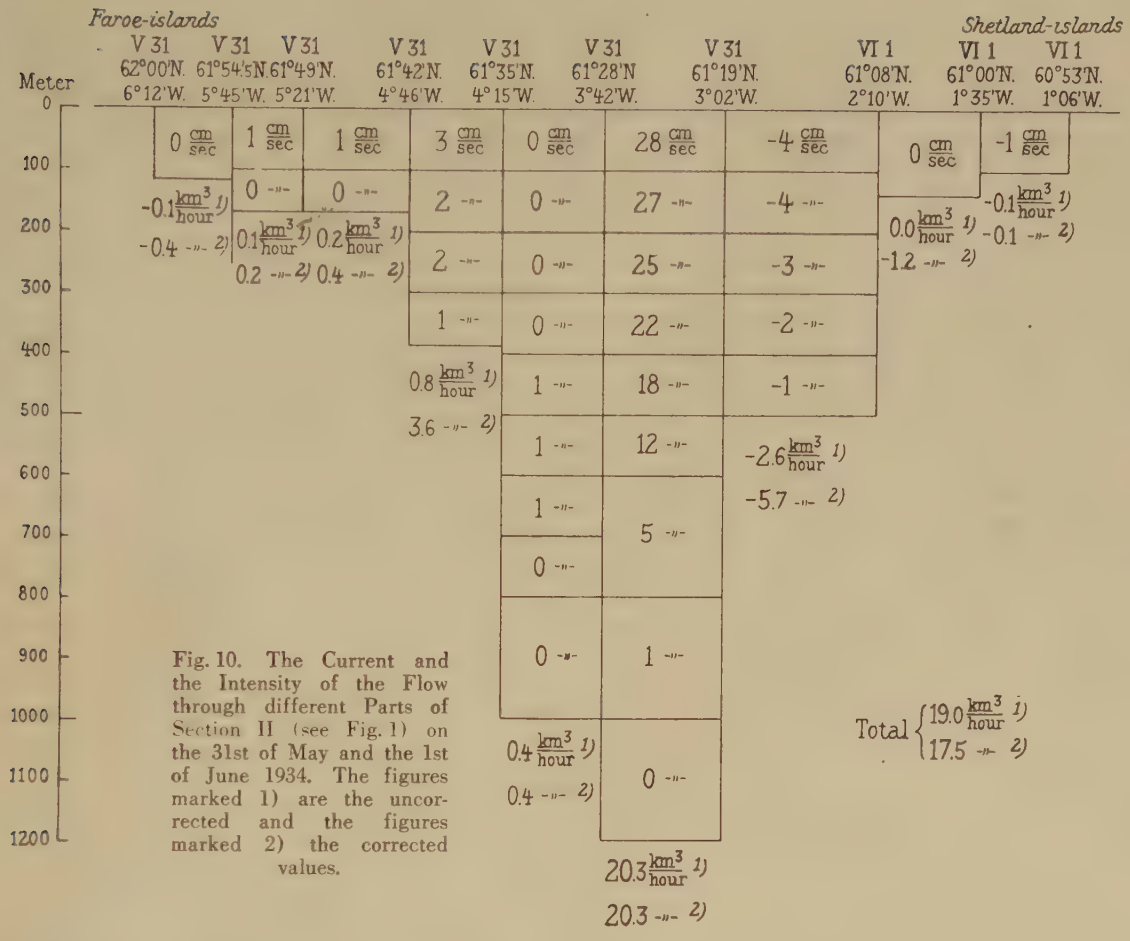


Fig. 10. The Current and the Intensity of the Flow through different Parts of Section II (see Fig. 1) on the 31st of May and the 1st of June 1934. The figures marked 1) are the uncorrected and the figures marked 2) the corrected values.

south-eastern side of the channel. In several other cases the water movement was found to deviate widely from the normal. In the north-western side of the channel currents with a southerly direction often appear.

Each time Sections I and II were investigated the intensity of the total flow through the sections was calculated as explained above for the cases shown in Figs. 8, 9 and 10. The "uncorrected" and the "corrected" values for the intensity of the flow are recorded in Table 4, Columns 4, 5, 9, and 10. The values are plotted in Figs. 11 and 12. At the bottom of Tab. 4 the mean values for the intensity of the total flow are recorded for each of the sections. Further the computed standard deviations of the mean values for the intensity of the total flow — the deviations from the mean being assumed to be accidental — are given at the bottom of the table.

As already mentioned, wind and tide must have some influence on the distribution of temperature and salinity and the shape of a solenoidal field at a given moment must therefore depend on these factors. Thus it was to be expected that the calculated values of the intensity of the flow through the channel would show co-variation with the wind and tide prevalent while the investigations took place. As an expression for the prevailing wind was used the difference between the heights of the barometer at the Hebrides (Stornoway) and East-Iceland (Berufjord and Seydisfjord) but no co-variation of these differences and the values for the intensity of the flow through the channel could be ascertained. This negative result cannot, however, be taken as a proof that co-variation does not exist, but must more probably be ascribed to the fact that the material is not suitable for a solution of the question. Nor can a co-variation of the tide and the intensity of the flow be found on the basis of the material at disposal. It is a well-known fact, however, that displacements of the water layers in the Faroe—Shetland Channel take place according to the tide. In 1910 Martin Knudsen[1])

[1]) Martin Knudsen: Danish Hydrographical Investigations at the Faroe Islands in the Spring of 1910. Medd. fra Komm. for Havunders., Bd. II, Nr. 1, 1911.

found vertical tidal movements amounting to about 100 m. at a depth of 400 m.

The air temperature and the surface temperature of the sea in the polar regions have increased considerably during the last twenty years. This is especially pronounced for the temperature of the winter months. According to R. Scherhag[2]) this rise in temperature is due to an increase in the atmospheric circulation. Ad. S. Jensen[3]) has shown that the change in temperature has been followed by changes in the fauna of the sea from Greenland in the west to Eurasia in the east. Possibly the intensity of the flow through the Faroe—Shetland Channel might be expected to have increased also during the last twenty years. This may be the case, but on the basis of the values for the intensity of the flow recorded in Tab. 4 it has not been possible to prove that such an increase actually exists.

On account of uncontrollable factors such as wind and tide the individual values for the intensity of the flow as given in Tab. 4 can be of small significance only. Thus conclusions, if any, must be based on mean values of certain groups of the individual values, the influence of the uncontrollable factors being to a certain degree eliminated in such means. Tab. 5 contains the means of the intensity of the flow through Sections I and II in the quarters April—May—June, July—August—September, and October—November—December.

The indications "uncorr." and "corr." at the head of the table refer to the method of determining the individual values for the intensity of the total flow, as explained in connection with Tab. 4. The number of values used for calculating the means is recorded in the table. The quarterly means for October—November—December may be left out of consideration, being based on three single values only. The other means are valid for spring and summer and show the average intensity of the total flow for these seasons to be 11·9 km.^{3}/hour. Probably the intensity of the flow increases from May to August, but the mean values in Tab. 5 cannot be taken as proof of such an increase.

In order to control the correctness of the calculations already mentioned the intensity of the total flow through Sections I and II in the quarters April—May—June, July—August—September and October—November—December was also calculated on the basis of Figs. 2a—c and 3a—c. The method adopted is explained in Chapter **F**, where it is exemplified by the calculation for Section II in the quarter April—May—June (see Tab. 17). The results of the calculations are given in Tab. 6.

Mean Values for the Intensity of the Total Flow (km.^{3}/hour) through the Faroe—Shetland Channel based in **Tab. 5** on the values in Tab. 4 and in **Tab. 6** on the Figs. 2a—c and 3a—c.

Medium-date:	Table 5. uncorr.	corr.	No.	Table 6.
Apr.—May—June				
Sect. I, 29. V	3·8	12·6	10	7·5
„ II, 26. V	6·9	8·7	18	14·2
July—Aug.—Sept.				
Sect. I, 12. VIII	3·7	10·0	11	13·1
„ II, 4. VIII	13·2	16·3	10	25·8
Oct.—Nov.—Dec.				
Sect. I, 25. XI	—0·1	4·2	3	2·5
„ II, 20. XI	6·4	14·1	3	16·8

The values for the intensity of the flow in Tabs. 5 and 6 should agree with each other but only a rough approximation is noted. As the deviations are due to the method of calculation, it may be of interest to consider the influence of a reasonably small change of the curves in one of the sections. Fig. 3b has been redrawn in Fig. 13 with altered positions of the isotherms and the isohalines in the right-hand side of the section, so that they reach the sea bottom at lesser depths in Fig. 13 than in Fig. 3b. In both figures the isotherms and the isohalines are drawn in close accordance with the mean values recorded in Table 3b, except that in Fig. 13 the singular observations 1·77° and 35·02 $^0/_{00}$ of temperature and salinity at 800 m. at Station 13A (see Tab. 3b) have been disregarded.

On the basis of the material at hand it is hardly possible to decide whether Fig. 3b or Fig. 13 should be preferred. The hypothesis applied in Fig. 13 that the isotherms and isohalines must rise to lesser depths before reaching the sea bottom is at least not unreasonable. The greatest sloping of the isotherms

2) R. Scherhag: Die Erwärmung des Polargebietes. Ann. d. Hydrogr. 1939, S. 57, Berlin.

3) Ad. S. Jensen: Concerning a change of climate during recent decades in the arctic and subarctic regions from Greenland in the west to Eurasia in the east and contemporary biological and geographical changes. Det Kgl. Danske Videnskabernes Selskab, Biol. Medd., XIV, 8, København, 1939.

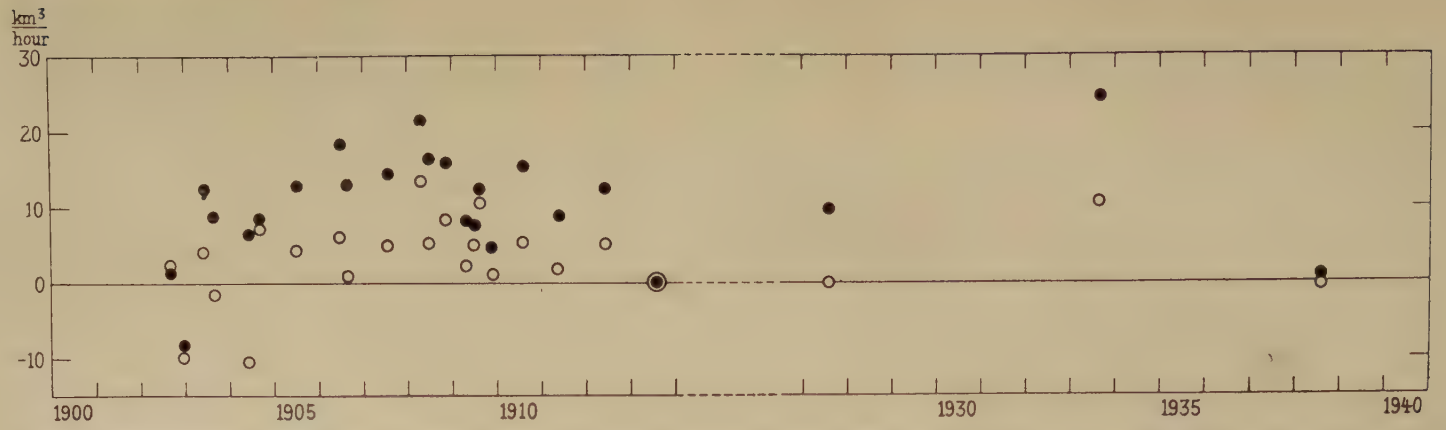


Fig. 11. Intensity of the Total Flow in a North-Easterly Direction through Section I (see Fig. 1). The uncorrected and the corrected values are represented by ○ and ● respectively.

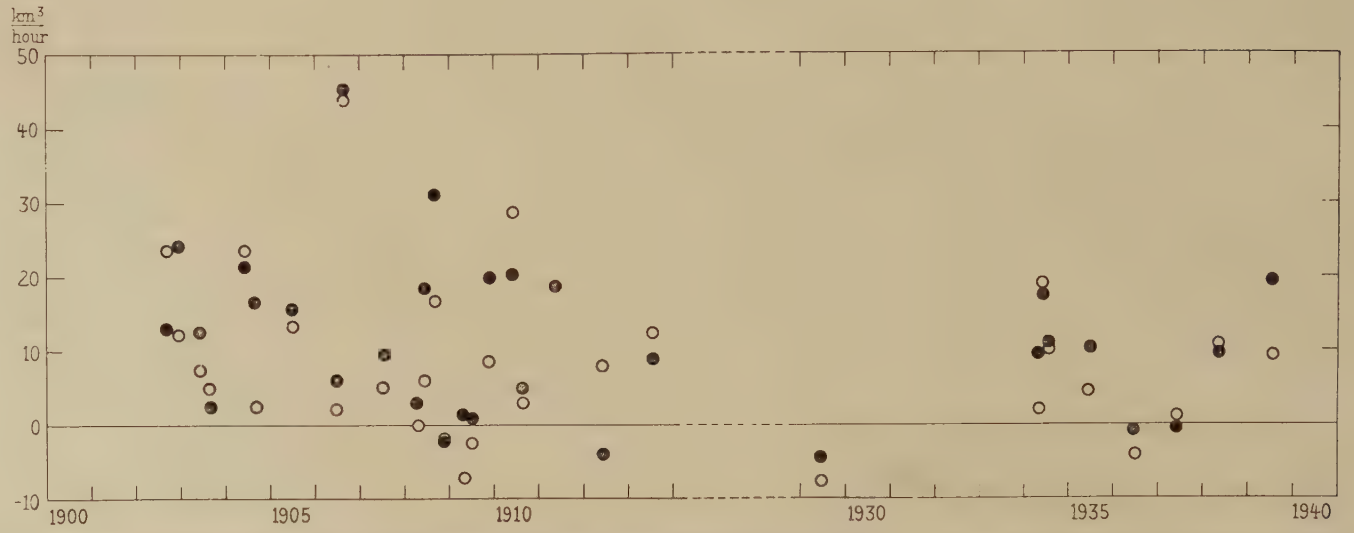


Fig. 12. Intensity of the Total Flow in a North-Easterly Direction through Section II (see Fig. 1). The uncorrected and the corrected values are represented by ○ and ● respectively.

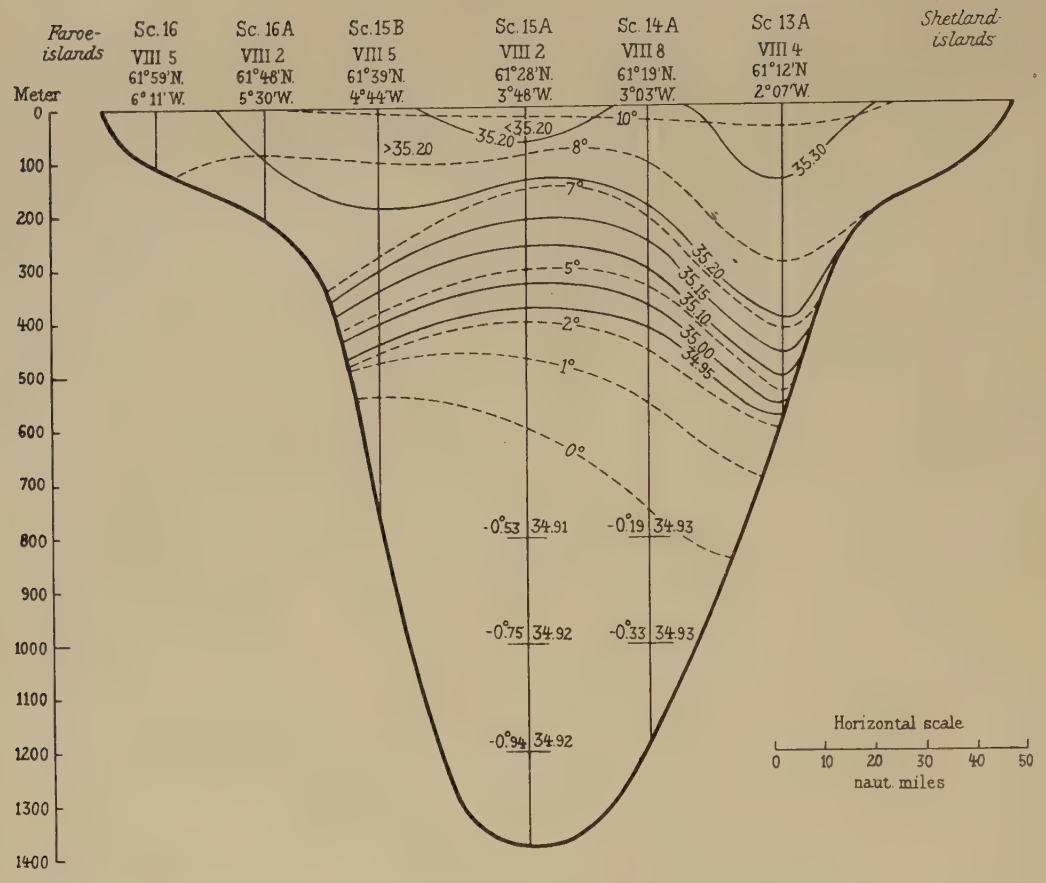


Fig. 13. Section II (see Fig. 1); July—August—September. The section is drawn on the basis of material from 10 cruises in July, August and September in the years 1902—39 similarly to Section II in Fig. 3 b, but with a modification in the course of the isotherms and the isohalines in relation to Section II in Fig. 3 b.

and isohalines in Fig. 13 is about 7 metres per kilometre. A calculation of the intensity of the total flow based on Fig. 13 gave as result 15·2 km.^{3}/hour instead of 25·8 km.^{3}/hour, as found from Fig. 3b and stated in Tab. 6. The value 15·2 km.^{3}/hour is in accordance with the value 16·3km.^{3}/hour given in Tab. 5 for Section II for the quarter July—August—September. Thus the discrepancies between Tabs. 5 and 6 may be explained by the uncertainty of the procedure employed in drawing them up.

As in Tab. 5 so also the values in Tab. 6 for the quarter October—November—December are of small importance, being based on three series of observations only. For the quarters April—May—June and July—August—September the values in Tab. 6 indicate a considerable increase in the intensity of the flow through the channel from May to August.

The values given in Tab. 6 indicate a greater intensity of the total flow through Section II than through Section I. Possibly this may be accounted for by the uncertainty of the procedure as discussed above. The reason, however, may also be that the zero-surface for Section II should have been chosen at a smaller depth, the flow in the lower part of Section II having a southerly direction. Between Sections I and II some vertical mixing of the water must take place and the greater part of the south-going water in Section II could then be carried northwards again before passing Section I. On the basis of the material at hand it is scarcely possible, however, to arrive at any decision on that problem.

If the values in Tab. 6 for the quarters April—May—June and July—August—September are regarded as equally good, then the mean value for the intensity of the total flow through the channel in these quarters will be 15·2 km.^{3}/hour. The mean value for the same quarters found from the values in Tab. 5 was 11·9 km.^{3}/hour.

In 1909 B. Helland-Hansen and F. Nansen[1]) found on the basis of solenoidal fields that the intensity of the total flow through the Faroe—Shetland Channel was between 125000 and 160000 km.^{3}/year or between 14 and 18 km.^{3}/hour. The above-stated values are not very different from those of Helland-Hansen and Nansen, which were based on a much smaller material.

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[1]) B. Helland-Hansen and F. Nansen. The Norwegian Sea. Rep. Norw. Fish. and Mar. Invest., Vol. II, 1909, No. 2, p. 170.

Table 7.

Intensity of Flow of Atlantic water ($S = 35{\cdot}45\ ^0/_{00}$, $t = 10{\cdot}2°$) in a north-easterly direction through Sections I and II (see Fig. 1).

Section I.

Year	Month	Intensity of flow km.³/hour uncorr.	corr.
1902	Aug.	1·3	1·0
„	Dec.	—4·0	—2·7
1903	May—June	3·4	7·7
„	Aug.	—1·0	5·7
1904	May	—5·8	4·8
„	Aug.	5·2	6·4
1905	June	3·3	8·5
1906	June	4·2	11·1
„	Aug.	1·0	8·3
1907	July	2·9	7·7
1908	April	7·8	11·3
„	June	3·3	9·4
..	Nov.	4·7	7·7
1909	April	1·9	7·1
„	June	3·5	5·0
„	Aug.	5·5	6·1
„	Nov.	0·8	3·1
1910	Aug.	4·6	11·5
1911	May	1·0	5·5
1912	June	3·4	7·1
1913	July	0·1	0·2
1927	Aug.	0·2	6·2
1933	Sept.	6·0	13·6
1938	Aug.	—0·1	1·4
—	—	—	—
—	—	—	—
—	—	—	—
—	—	—	—
—	—	—	—
—	—	—	—
—	—	—	—
Mean value		2·2	6·4
Standard deviation		0·6	0·8

Section II.

Year	Month	Intensity of flow km.³/hour uncorr.	corr.
1902	Aug.	11·8	8·2
„	Dec.	6·3	13·1
1903	May	4·0	6·5
„	Aug.	2·6	1·3
1904	May	14·2	12·9
„	Aug.	2·2	9·6
1905	June	9·5	10·9
1906	June	1·3	3·1
„	Aug.	20·1	21·8
1907	July	2·8	4·6
1908	April	2·8	5·1
„	June	3·4	10·4
„	Aug.	4·8	9·2
„	Nov.	1·8	1·1
1909	April	0·9	5·1
„	June	1·1	1·8
„	Nov.	4·7	9·7
1910	May	10·7	8·4
„	Aug.	1·7	2·3
1911	May	10·8	10·8
1912	May	4·4	—0·5
1913	July	5·4	4·0
1929	June	0·3	2·6
1934	April	1·1	4·5
„	May—June	10·7	9·0
„	July	3·4	4·4
1935	June	4·0	8·5
1936	June	—2·1	0·8
1937	May	1·4	0·4
1938	May	6·2	7·9
1939	July	7·7	13·2
Mean value		5·2	6·8
Standard deviation		0·9	0·9

D. The Intensity of the Flow of Atlantic Water ($t = 10{\cdot}2°$, $S = 35{\cdot}45\ ^0/_{00}$) through the Faroe—Shetland Channel.

As mentioned in Chapter **B**, the water passing through the Faroe—Shetland Channel into the Norwegian Sea mainly consists of two components, i.e., $t = 10{\cdot}2°$, $S = 35{\cdot}45\ ^0/_{00}$ and $t = 2{\cdot}5°$, $S = 34{\cdot}90\ ^0/_{00}$. The former is often referred to in the sequel as "Atlantic water". In this chapter it is explained to what extent the inflow into the Norwegian Sea through the Faroe—Shetland Channel consists of Atlantic water of the stated qualities.

It has been described in Chapter **C** how the current and the intensity of the flow were calculated for the different depth intervals between stations in Sections I and II at the different times of the year when the investigations were carried out. The diagrams in Figs. 8, 9 and 10 were given as examples of the results of these calculations. For arbitrary depth intervals, such as those shown in Figs. 8, 9 and 10, we designate the intensity of the flow by q, the mean salinity by S_m and the mean temperature by t_m. On the assumption that the water consists of the above-stated components the intensity q_A of the flow of the Atlantic water alone through the interval may be determined by the expressions:

$$q_A = q\,\frac{S_m - 34{\cdot}90}{0{\cdot}55} \quad \text{and} \quad q_A = q\,\frac{t_m - 2{\cdot}5}{7{\cdot}7}$$

In these expressions no account has been taken of the fact that the salinity and the temperature of the upper layers are to some degree influenced by the difference between precipitation and evaporation and by the exchange of heat between the sea and the atmosphere. The most reliable value for q_A

is undoubtedly found by the first of the above expressions.

Tab. 7 contains the values for the intensity of the flow of Atlantic water through Sections I and II. The values under the heading "uncorrected" have been found by adding-up the products of the intensity q of the flow and the quotient $\frac{S_m - 34{\cdot}90}{0{\cdot}55}$ for the different intervals in the whole section, disregarding the solenoidal field below the zero-surface, which for each pair of stations was chosen at — or near — the bottom at the station with the smaller depth.

Mean values for the intensity of the flow of the Atlantic water are given at the bottom of the table. The standard deviations of the means recorded below these are found on the supposition that the deviations from a mean may be regarded as accidental. The means of the uncorrected values are 2·2 and 5·2 km.^{3}/hour for Sections I and II respectively. Analogous computations by means of the second of the above expressions containing t_m instead of S_m gave the results 2·6 and 5·5 km.^{3}/hour respectively.

The values for the intensity of the flow of the Atlantic water through the Sections I and II under the heading "corrected" in Tab. 7 are found on the supposition that a surface consisting of the isobaric surface at the depth of 800 m. and the bottom of the sea for depths less than 800 m. could be taken as zero-surface for the section in question.

For each pair of stations the correction k to be added to the uncorrected value for the flow of Atlantic water was found by the expression:—

$$k = 0{\cdot}925 \cdot 10^{-10} cg \cdot \Delta r \cdot 0{\cdot}364 (d'_z - d'_r) \Big[(S_{50} - 34{\cdot}90) + (S_{150} - 34{\cdot}90) + \ldots + \left(\frac{S_{100n} + S_r}{2} - 34{\cdot}90 \right) \cdot \frac{d'_r - 100\, n}{100} + 0{\cdot}0033 (S_r - 34{\cdot}90)(d'_z - d'_r) \Big]$$

which was derived by means of expressions (30) and (32) in Chapter **F**. Besides the symbols in the above expression, explained in Chapter **F**, the Symbols S_{50}, S_{150} .... are used for the mean salinity between the stations considered at the depths 50, 150 ... metres. S_r represents the mean salinity at the depth d'_r metres, where d'_r is the depth of the zero-surface first chosen and S_{100n} the mean salinity at a depth of 100 n metres, where n is an integer number and where

$$100\, n < d'_r < 100\ (n + 1).$$

The depth d'_z refers to the station with the greatest depth but if that depth was greater than 800 m. d'_z was equalized to 800 m. It has been supposed that the mean salinity of the water

Fig. 14.

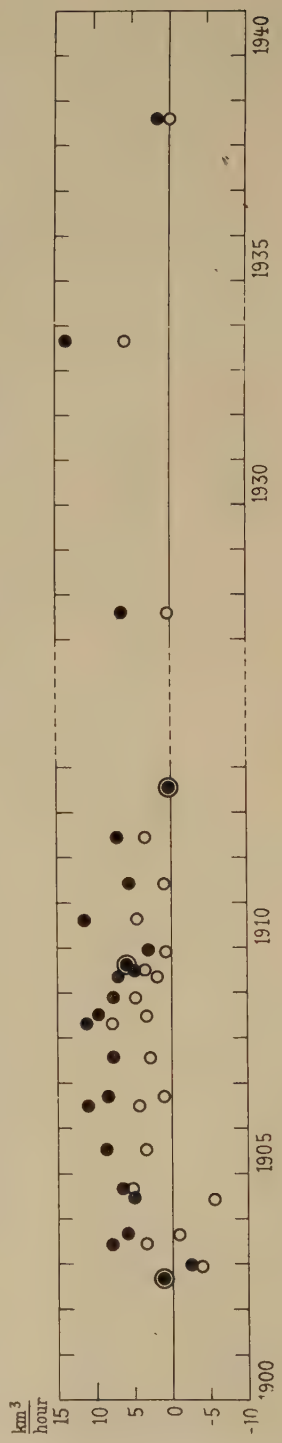


Fig. 15.

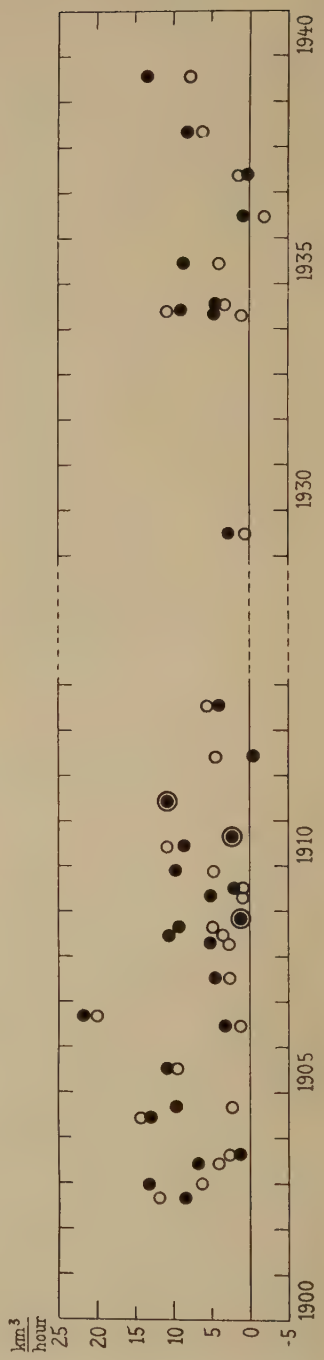


Fig. 14. Intensity of Flow of Atlantic Water through Section I (see Fig. 1). The uncorrected and the corrected values are represented by ○ and ● respectively.

Fig. 15. Intensity of Flow of Atlantic Water through Section II (see Fig. 1). The uncorrected and the corrected values are represented by ○ and ● respectively.

below the zero-surface first chosen could be equalized to the mean salinity at that surface. The uncorrected as well as the corrected values for the intensity of the flow of Atlantic water through Sections I and II are plotted in Figs. 14 and 15.

The means 6·4 and 6·8 km.³/hour for the corrected values of the intensity of the flow of Atlantic water through Sections I and II as stated at the bottom of Tab. 7 are in good accordance. The deviations from the means do not show any regularity; and as far as can be seen from the material considered, they must be regarded as accidental.

Analogous to Tab. 5, valid for the whole amount of water passing through the Faroe—Shetland Channel, Tab. 8 has been prepared for the Atlantic water alone.

Table 8.

Mean Values for the Intensity of the Flow (km.³/hour) of Atlantic Water, $t = 10{\cdot}2°$, $S = 35{\cdot}45\ ‰$, through the Faroe—Shetland Channel, based on the values in Tab. 7.

	Uncorrected	Corrected	No.
Apr.—May—June			
Section I	2·6	7·8	10
„ II	4·7	6·0	18
July—Aug.—Sept.			
Section I	2·3	6·2	11
„ II	6·2	7·9	10
Oct.—Nov.—Dec.			
Section I	0·5	2·7	3
„ II	4·3	8·0	3

E. The Geographical Distribution of Atlantic Water (t 10·2°, S — 35·45 ‰) in the northern part of the North Sea, the Norwegian Sea and the Barents Sea.

Atlantic water ($t = 10{\cdot}2°$, $S = 35{\cdot}45\ ‰$), mainly in diluted form, is carried through the Faroe—Shetland Channel into the Norwegian Sea and the adjacent waters. According to our preceding calculations the intensity of the flow of unmixed Atlantic water averages 6·6 km.³/hour. The geographical distribution of this water in a vertical and horizontal direction in the northern part of the North Sea, the Norwegian Sea and the Barents Sea will be discussed in this chapter together with questions concerning its renewal in the course of time.

Let us assume that the Atlantic water — characterized by $t = 10{\cdot}2°$, and $S = 35{\cdot}45\ ‰$ — were separated from the rest of the water in the northern part of the North Sea, the Norwegian Sea, and the Barents Sea and that no horizontal displacements could take place during the separation. The Atlantic water would then be collected in one or more limited water layers. The thickness of such a separate layer of Atlantic water at an arbitrarily chosen place is termed *the equivalent thickness of Atlantic water* in its diluted condition at the place.

The equivalent thickness of Atlantic water at a hydrographical station can be found by means of the TS-diagram for the station. Fig. 16 shows a TS-diagram for a station at 63°00′5 N., 3°46′ E. taken from the "Johan Hjort" on May 1st, 1935. The points plotted in the diagram show the observed values of temperature and salinity at the station. The figures at these points indicate the depths in hectometres. The TS-curve has been drawn with a slight smoothing. The straight dotted line between the points representing the components $t = 10{\cdot}2°$, $S = 35{\cdot}45\ ‰$ and $t = 2{\cdot}5°$, $S = 34{\cdot}90\ ‰$ is divided into ten equal parts by marks indicating the fractions $\frac{1}{10} + \frac{9}{10}$, $\frac{2}{10} + \frac{8}{10}$ etc. of the two components.

The TS-curve for depths from 50 to 400 m. follows the straight dotted line rather closely, indicating that the water at that depth interval mainly consists of the above-stated components. For the interval from 50 to 250 m. the plotted points are situated below the straight dotted line. This is probably due to the winter cooling. On TS-diagrams for stations taken in autumn the points representing the temperature and salinity in the upper layers were often situated above the straight dotted line in accordance with the heating during summer.

By means of diagrams such as that shown in Fig. 16 the fractions of the component $t = 10{\cdot}2°$, $S = 35{\cdot}45\ ‰$ at different depths of the stations were read. From Fig. 16 the following readings were obtained:

Depth in metres:	Fraction of the component $t = 10{\cdot}2°$, $S = 35{\cdot}45\ ‰$
0	0·00
50	0·73
150	0·67
200	0·60
250	0·57
300	0·43
400	0·04
410	0·00

The equivalent thickness of the Atlantic water at the station is then calculated to be:

$0{\cdot}5 \cdot 0{\cdot}73 \cdot 50 + 0{\cdot}70 \cdot 100 + 0{\cdot}64 \cdot 50 + 0{\cdot}58 \cdot 50 + 0{\cdot}50 \cdot 50 + 0{\cdot}24 \cdot 100 + 0{\cdot}02 \cdot 10 = 198$ metres.

The method illustrated by the example above was principally used at the determination of the equivalent thickness of Atlantic water at all the stations in question. In several cases rather large deviations between the TS-curves and the straight line representing the mixing products of the two components were found. Such deviations could in

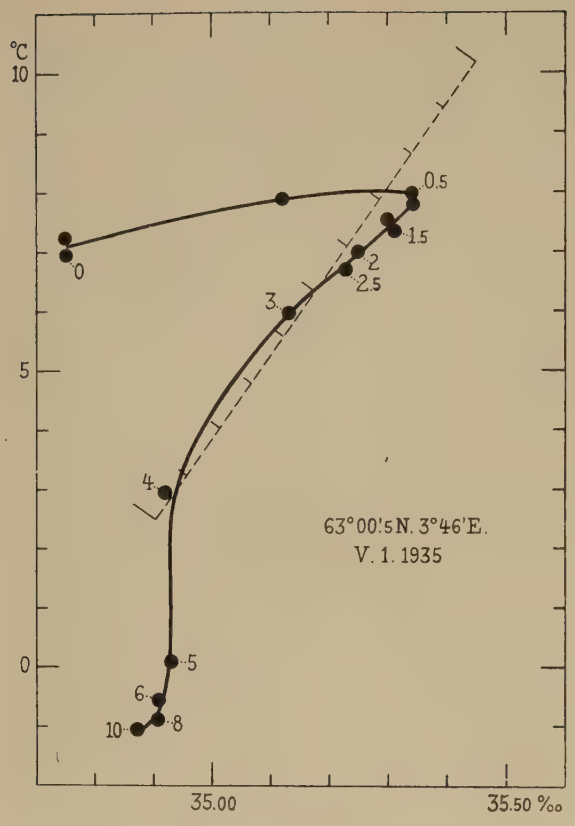


Fig. 16.

some cases be explained as due to heating from the atmosphere and from sun radiation. In other cases their cause was to be found in the fact that the water did not consist of the above-stated components only, but had also been influenced by water of other qualities. If a deviation could with a fair degree of certainty be ascribed to heating from the atmosphere and sun radiation the fraction of the Atlantic water was estimated from the temperature that should have occurred without heating. In other cases where no definite reason could be given for a deviation of the TS-curve that fraction only of Atlantic water which could be ascertained with a high degree of probability was taken into consideration. The difficulties in determining the fraction of Atlantic water were usually of no great importance at the determination of the equivalent thickness of Atlantic water at the stations.

The limits that were found in the way described for the extension of Atlantic water are not to be taken as absolute. In fact a diffusion of Atlantic water into the surrounding water masses takes place as a result of mixing processes. The amount of Atlantic water disappearing by this mixing during a certain long period of time must be equal to the amount of Atlantic water carried through the Faroe—Shetland Channel during the same period of time.

The equivalent thickness of the Atlantic water in the Norwegian Sea and in the Barents Sea was calculated by the method described for each of the stations from which series of temperature and salinity determinations were at disposal and from which the existence of Atlantic water could be ascertained.

The calculated values of the equivalent thickness of the Atlantic water were arranged on forms according to areas of 1° of latitude × 1° of longitude and according to the quarters January—February—March, April—May—June, July—August—September and October—November—December. For each of the fields the quarterly means were calculated and recorded on maps — with ten metres as a unit — together with the number of values used for each of the means. These maps are reproduced as Figs. 17—20. Means were also calculated for each of the fields on the basis of the whole material and similarly recorded (Fig. 21).

The equivalent thickness of the Atlantic water in the northern North Sea was found by means of the maps of Martin Knudsen[1]) showing the mean salinity at different depths in the North Sea. As these maps are constructed on the basis of the material from the whole year, the equivalent thickness of the Atlantic water could be given for the whole year only. The calculated values for the equivalent thickness of the Atlantic water in the northern North Sea are given on the maps in Figs. 17—21 in spite of the fact that they refer to the whole year only while the other parts of Figs. 17—20 refer to the quarters of the year.

On the maps in Figs. 17—21 curves marked 0, 5, 10, 15, and 20 are drawn through the places where the equivalent thickness of the Atlantic water was estimated to average 0, 50, 100, 150, and 200 m. respectively. Thereby some irregularities estimated to be inessential were not considered. Inside the curve marked 20 the equivalent thickness of the Atlantic water may be taken as equal to 200 m. Outside the curve marked 0 the Atlantic water could not be ascertained by the method described.

Probably a seasonal variation exists in the extension of the Atlantic water, but the evidence of such a variation has not come out very clearly at the treatment of the material.

Figs. 17—21 show the characteristic distribution of Atlantic water in the Norwegian Sea and adjacent waters. Having passed the Faroe—Shetland Channel it chiefly follows the Norwegian coast and is especially conspicuous in the area off Lofoten. In the coastal regions off Norway it is strongly mixed with water originating from the Baltic and from land. The curve indicating the equivalent thickness 100 m. is, however, situated at a short distance from

[1]) Bulletin Hydrographique 1906—1907, Partie supplémentaire.

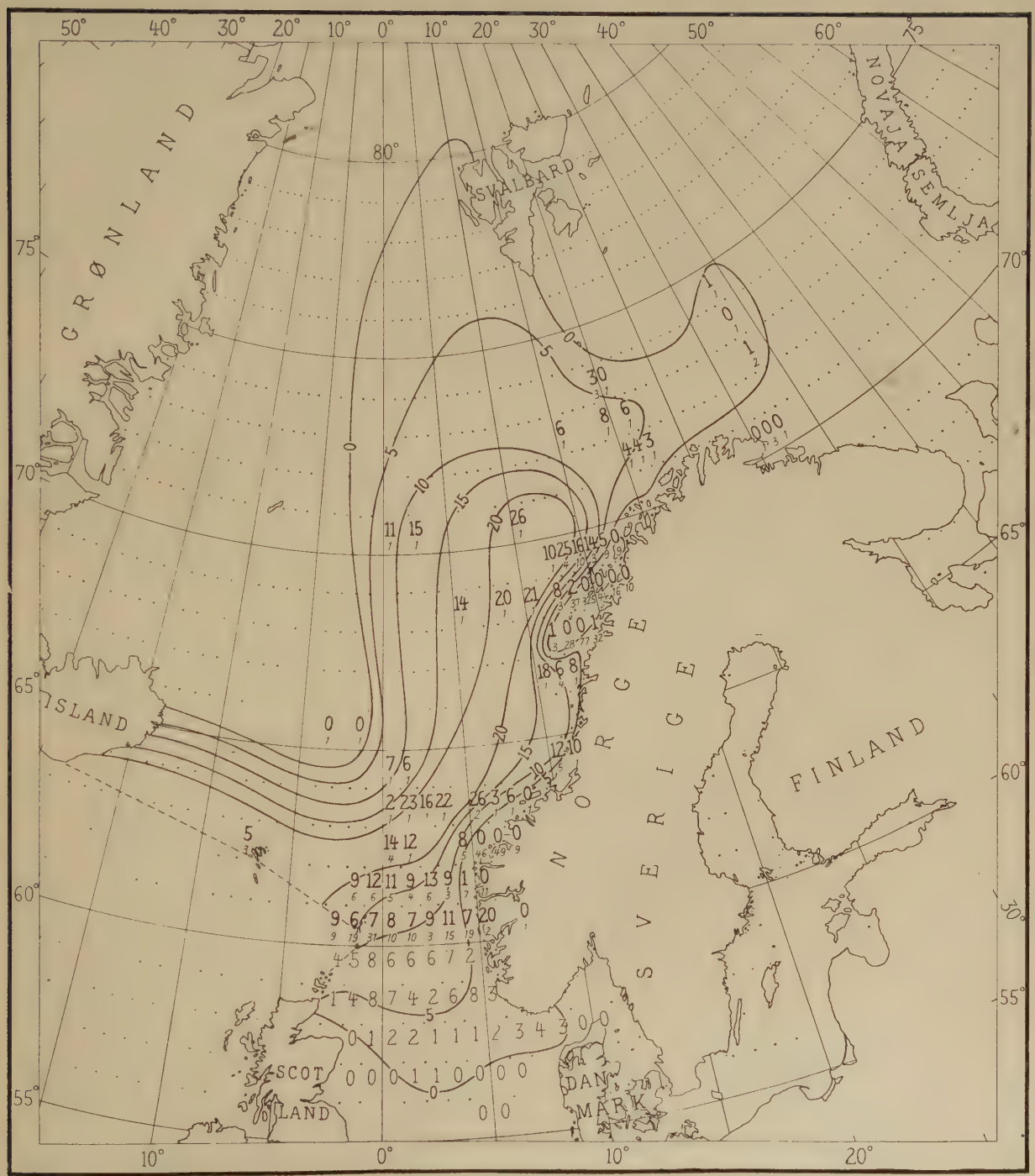


Fig. 17. The Equivalent Thickness — see p. 23 — of the Atlantic water, $t = 10{\cdot}2°$, $S = 35{\cdot}45\ ‰$, in the months January—February—March. The heavy figures indicate mean values of the Equivalent Thickness with 10 metres as unit. The *small* figures below the heavy ones give the number of series of observations used in calculating the means.

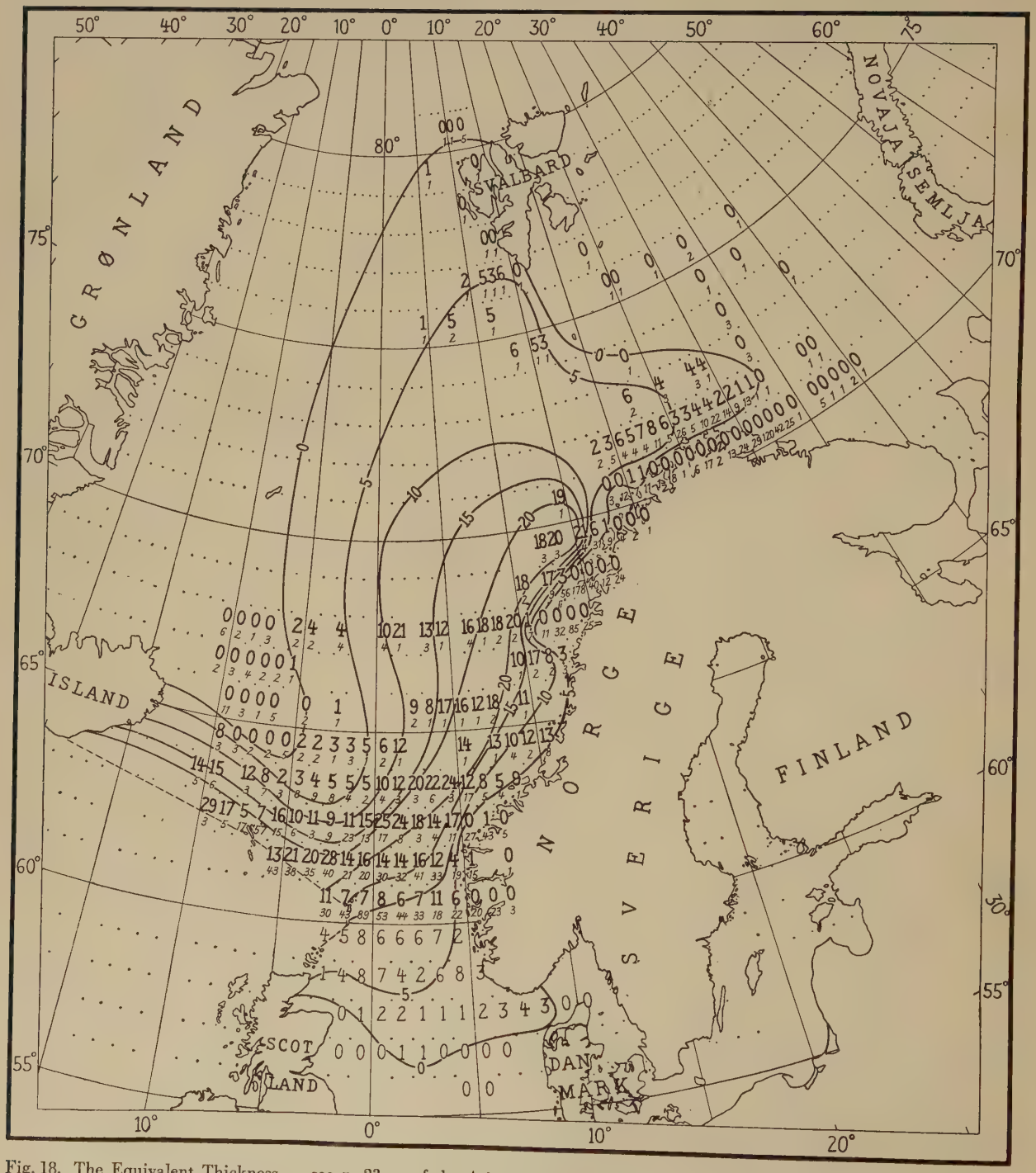


Fig. 18. The Equivalent Thickness — see p. 23 — of the Atlantic water, $t = 10{\cdot}2°$, $S = 35{\cdot}45$ ‰, in the months April—May—June. The heavy figures indicate mean values of the Equivalent Thickness with 10 metres as unit. The *small* figures below the heavy ones give the number of series of observations used in calculating the means.

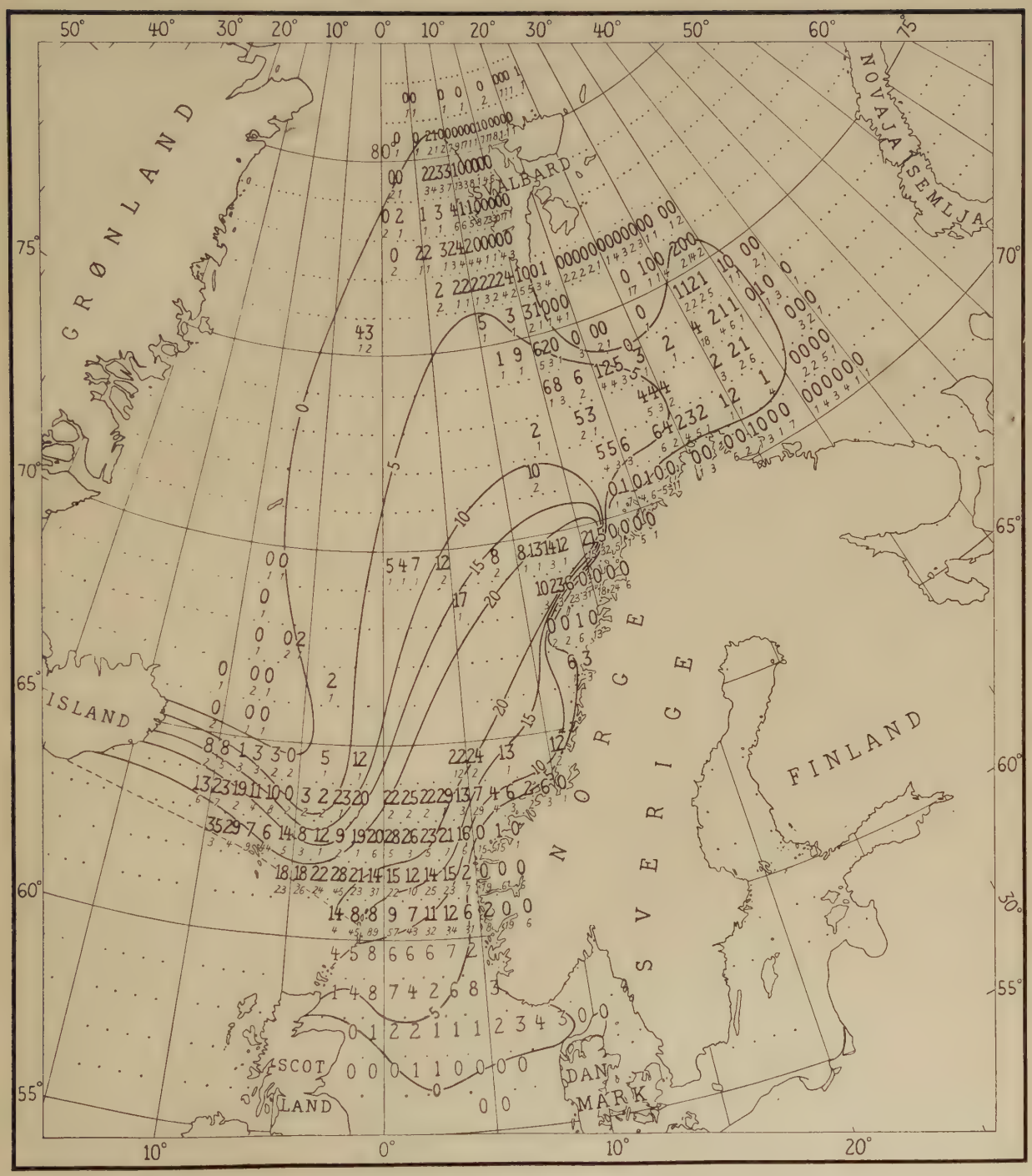


Fig. 19. The Equivalent Thickness — see p. 23 — of the Atlantic water, $t = 10{\cdot}2°$, $S = 35{\cdot}45\ ‰$, in the months July—August—September. The heavy figures indicate mean values of the Equivalent Thickness with 10 metres as unit. The *small* figures below the heavy ones give the number of series of observations used in calculating the means.

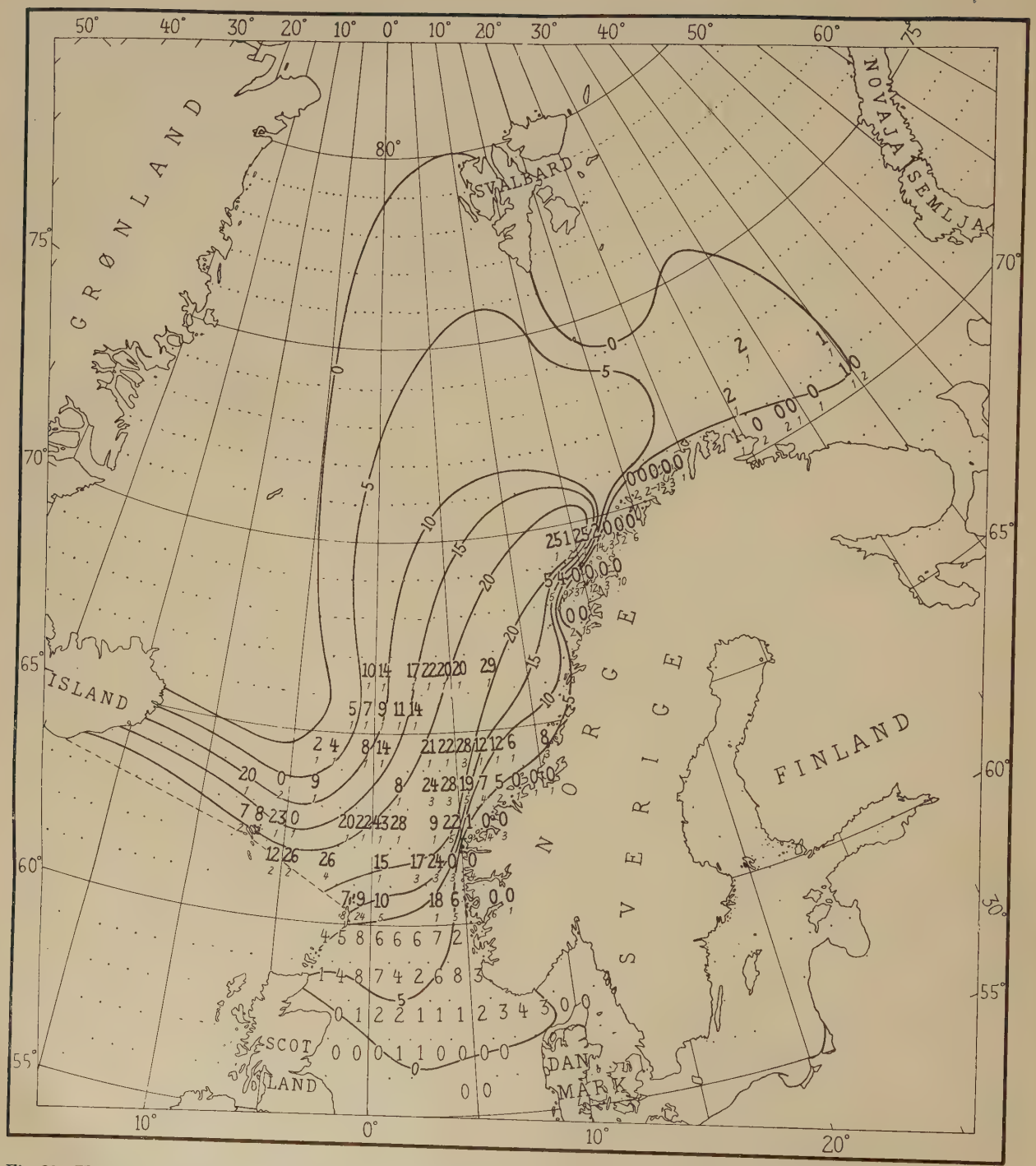


Fig. 20. The Equivalent Thickness — see p. 23 — of the Atlantic water, $t = 10{\cdot}2°$, $S = 35{\cdot}45$ ‰, in the months October—November—December. The heavy figures indicate mean values of the Equivalent Thickness with 10 metres as unit. The *small* figures below the heavy ones give the number of series of observations used in calculating the means.

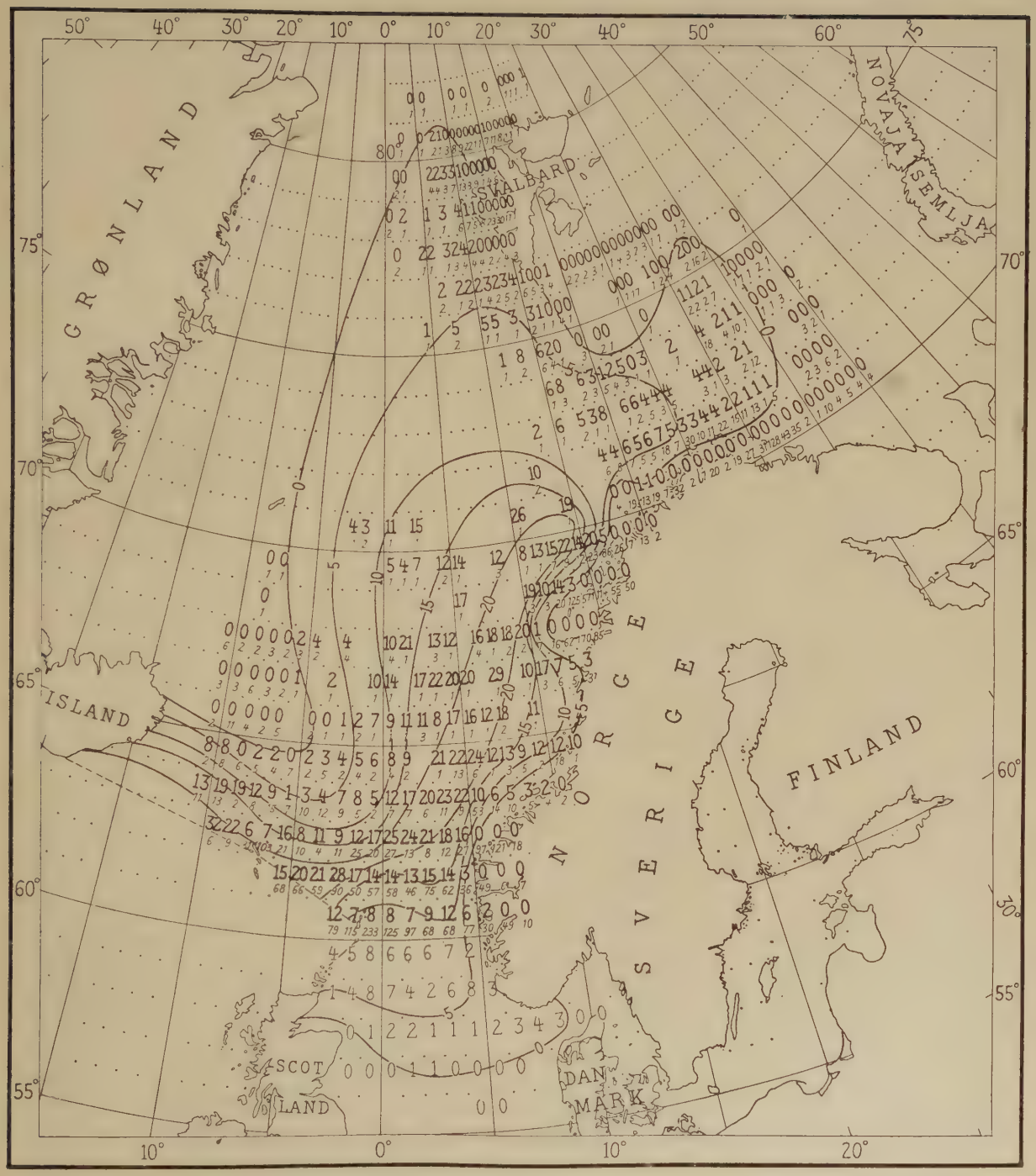


Fig. 21. The Equivalent Thickness — see p. 23 — of the Atlantic water, $t = 10{\cdot}2°$, $S = 35{\cdot}45\ ‰$, found on the basis of the whole material. The heavy figures indicate mean values of the Equivalent Thickness with 10 metres as unit. The *small* figures below the heavy ones give the number of series of observations used in calculating the means.

the coast. Towards the west it extends approximately to 5° W. Long. Off-shoots are found in the Barents Sea and in the area west of Svalbard.

The southern limit of the area in which the extension of Atlantic water has been considered is drawn from the Shetland Islands to the Faroe Islands and from there to the southern coast of Iceland. The volume of this water inside this limit and the curves showing the equivalent thickness 0, 50, 100, 150, and 200 m. were calculated from the sizes of the areas and the mean values of the equivalent thickness of the water within the areas. The results of the calculations are given in Table 9.

In the preceding chapter it was found that the intensity of the flow of Atlantic water through the Faroe—Shetland Channel into the Norwegian Sea averaged 6·6 km.^{3}/hour. This supply of Atlantic water to the Norwegian Sea must, in course of time, pass through the sections which in Figs. 17—21 can be laid through the lines from the Shetland Islands to the Faroe Islands and from there to the southern coast of Iceland and through the curves showing the equivalent thickness 200, 150, 100, 50 and 0 m. in these figures. A kind of mean values for the time of the renewal of the Atlantic water under consideration in the different areas may be found if it is supposed that the spreading of the Atlantic water takes place continuously from the area inside the 200-metre curve to the area between the 150 and the 100-metre curve, and so on. The mean values calculated on this supposition are given in Tab. 10. The column marked 0 shows the time necessary for the renewal of the whole amount of Atlantic water under consideration.

Table 9.

The Volume — given in 1000 km.^{3} as unit — of Atlantic Water, $t = 10{\cdot}2°$, $S = 35{\cdot}45\ ^0/_{00}$, inside areas limited in Figs. 17—21 by the lines from the Shetland Islands to the Faroe Islands and from there to the southern coast of Iceland, and by the curves showing the equivalent thickness 200, 150, 100, 50 and 0 m.

	Curves limiting the areas	Equivalent thickness in metres					
		200	200—150	150—100	100—50	50—0	0
Fig. 17.	Jan.—Febr.—March	54	40	30	32	16	172
Fig. 18.	April—May—June	38	35	35	41	18	167
Fig. 19.	July—August—Sept.	50	36	27	40	22	175
Fig. 20.	Oct.—Nov.—Dec.	47	41	26	42	20	176
Fig. 21.	The whole material	46	39	32	43	21	181

Table 10.

Mean Values for the Time of Renewal — given in years — of Atlantic Water, $t = 10{\cdot}2°$, $S = 35{\cdot}45\ ^0/_{00}$, inside the areas limited in Figs. 17—21 by the lines from the Shetland Islands to the Faroe Islands and from there to the southern coast of Iceland, and by the curves showing the equivalent thickness 200, 150, 100, 50 and 0 m.

	Curves limiting the areas	Equivalent thickness in metres					
		200	200—150	150—100	100—50	50—0	0
Fig. 17.	Jan.—Febr.—March	0·94	0·69	0·51	0·55	0·27	2·96
Fig. 18.	April—May—June	0·66	0·60	0·60	0·71	0·31	2·88
Fig. 19.	July—August—Sept.	0·87	0·62	0·47	0·70	0·38	3·04
Fig. 20.	Oct.—Nov.—Dec.	0·81	0·70	0·45	0·73	0·34	3·03
Fig. 21.	The whole material	0·79	0·68	0·55	0·75	0·35	3·12

Tab. 10 shows that the renewal of the Atlantic water in the Norwegian Sea and adjacent waters must on the average take about three years and that the renewal of the Atlantic water inside the central area, limited by the lines Shetland Islands—Faroe Islands—south coast of Iceland and by the curve showing the equivalent thickness 200 m. must take about 9 months. According to these results one would think that *the flora and fauna in different localities in the Norwegian Sea and adjacent waters depended to a higher degree on local displacements of the Atlantic water — characterized by $t = 10{\cdot}2°$ and $S = 35{\cdot}45\ ^0/_{00}$ — than on the variations in the flow of that water through the Faroe—Shetland Channel.*

The influence of the Atlantic water on the hydrographical conditions in the Norwegian Sea was discussed already in 1909 by Bjørn Helland-Hansen and Fridtjof Nansen[1]).

[1]) Bjørn Helland-Hansen and Fridtjof Nansen: The Norwegian Sea. Rep. Norw. Fish. and Mar. Invest., Vol. II, 1909, No. 2, p. 170.

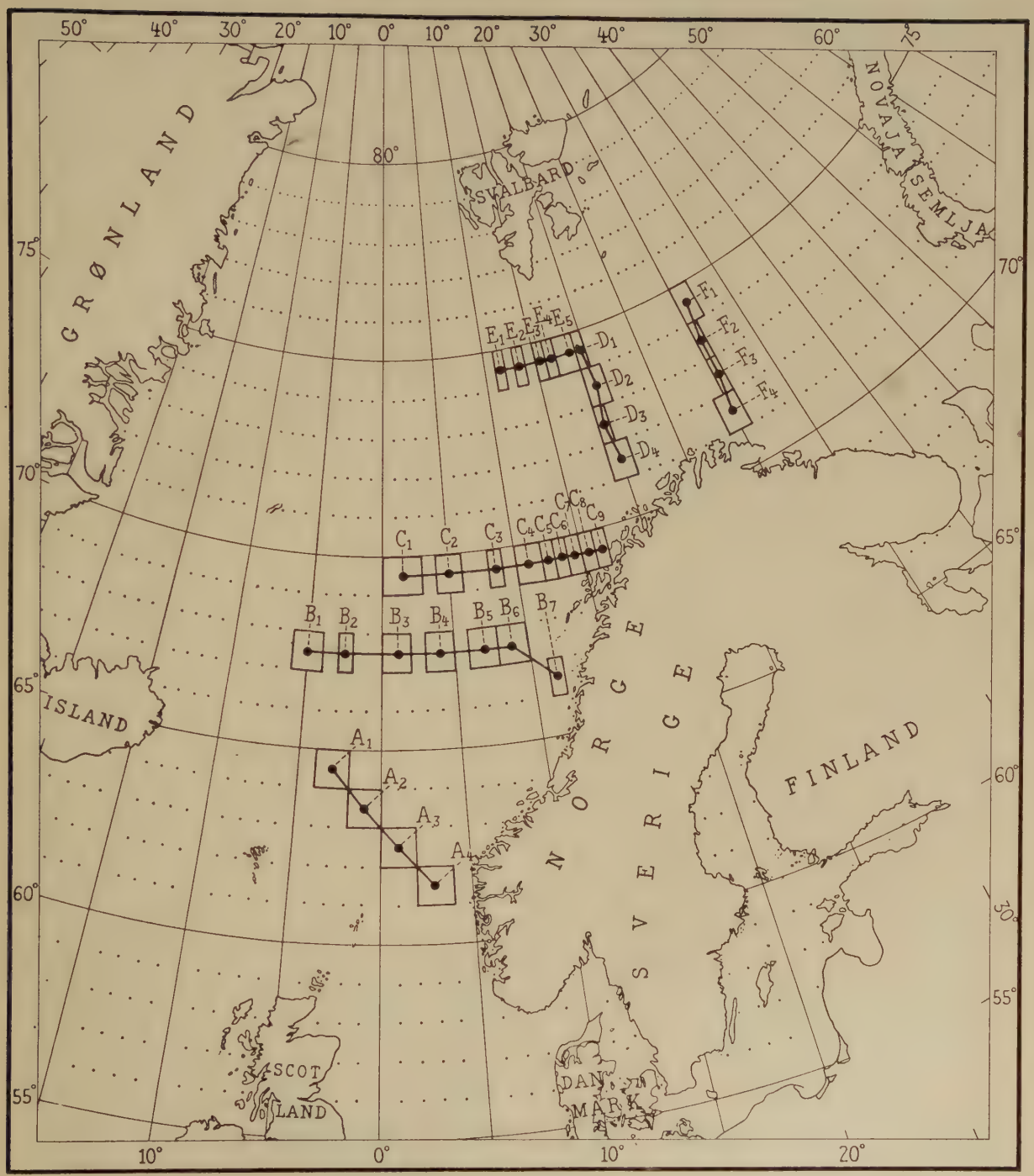


Fig. 22. Areas used in the Determination of the Vertical Distribution of the Atlantic Water, $t = 10{\cdot}2°$, $S = 35{\cdot}45\ ‰$

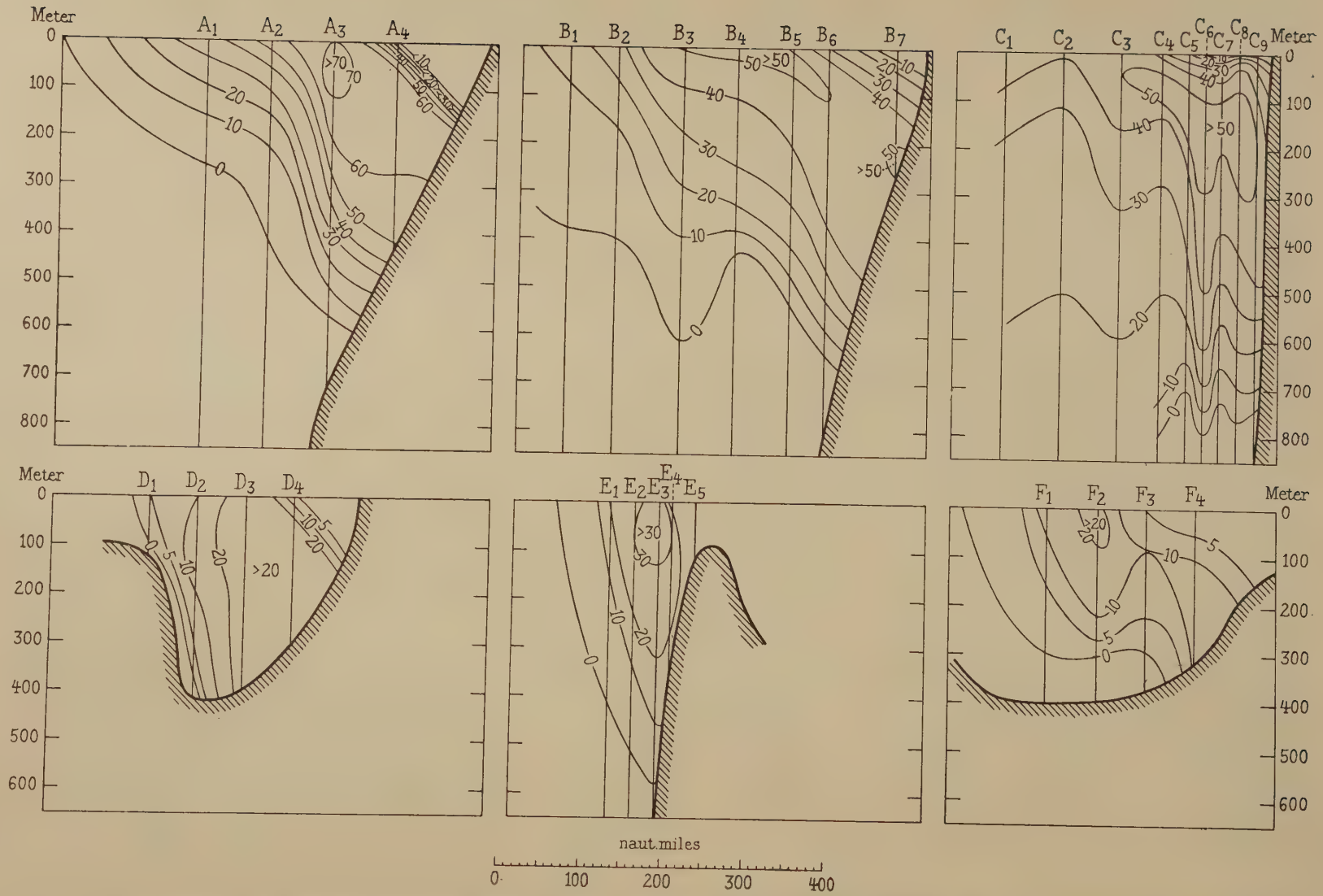


Fig. 23. Sections showing the Distribution of Atlantic Water, $t = 10{\cdot}2°$, $S = 35{\cdot}45$ ‰. The figures on the curves indicate the percentage of Atlantic Water. The position of the sections is shown in Fig. 22.

These authors pointed out that the renewal of the Atlantic water in the Norwegian Sea was comparatively slow and that its extension was greater than might be expected if the Atlantic current followed a straight course.

The vertical extension of the Atlantic water, $t = 10{\cdot}2°$ and $S = 35{\cdot}45\ ‰$, in the northern North Sea, the Norwegian Sea, and the Barents Sea was investigated by means of the TS-diagrams already used for the determination of the equivalent thickness of the Atlantic water. The map in Fig. 22 shows the areas from which the material was used. Each of these areas consists of one or a few one-degree fields only. The centre-positions of the areas are marked with the letters A — F with the indices 1, 2, 3, ... The available TS-diagrams were divided into groups according to the areas. The fractions of the Atlantic water at different depths were determined from the diagrams as explained in connection with Fig. 16. For each group the fractions were averaged for each of the depths. The means of the fractions were taken as valid for the places given by the centre-positions of the areas. The depths at which the fractions were 0·00, 0·05, 0·10, 0·20 ... were determined graphically and used for the construction of Fig. 23, where the vertical distribution of the Atlantic water is shown for sections laid through the centre-positions of the areas in each of the groups. The sections in Fig. 23 are marked in accordance with Fig. 22. The curves in the sections are drawn through the depths where the percentage of the Atlantic water was found to be 0, 5, 10, 20 ... %.

Fig. 23 clearly illustrates the gradual mixing of the Atlantic water with the surrounding waters as it moves northwards. Off Lofoten the core of the current still contains about 50 % of Atlantic water, while but 20—30 % are left when it reaches the area between Svalbard and Norway. Usually the core of the Atlantic water is covered by mixed water of a lower percentage.

It is evident that the amount of heat carried through the Faroe—Shetland Channel with the flow of Atlantic water is partly spent in heating the surrounding water masses in the Norwegian Sea. Part of the heat must be absorbed by the air, and so to some extent influence the climate of the coastal regions surrounding the northern ocean, but *most likely this influence is of minor importance when compared with the heating from the air-currents reaching these regions from more southerly latitudes.*

F. Procedure in the Calculation of Currents and Intensity of Flow through a Section, based on an existing Solenoidal Field, with special reference to the Hydrographical Conditions in the Faroe—Shetland Channel.

The temperature and salinity at the same series of depths at two hydrographical stations are presumed to be known. In the calculation of the currents at a right angle to a section through the two stations by means of the V. Bjerknes'[1]) method, the differences between the specific volumes at the stations must be utilized. We designate the stations by H′ and H″ and the specific volumes at the stations in an isobaric surface, where the pressure involved by the sea water alone — disregarding the atmospheric pressure — is p decibars, by the symbols $\alpha_{S',t',p}$ and $\alpha_{S'',t'',p}$, the indices indicating the relevant values of salinity, temperature and pressure. An isobaric surface at a depth of d metres — taken as the distance from the surface of the sea at station H′ — must at station H″ be situated at a depth ordinarily deviating from d metres. At the surface of the sea the deviation is nil and for isobaric surfaces at the depth in the Faroe—Shetland Channel area it may increase to a maximum of 30 centimetres at the utmost. Observations of temperature and salinity at the same depth at two stations, therefore, may be taken as valid for the isobaric surface at the observation depth at one of the stations.

Using the rounded-off value 0·973 for the specific volume of the sea water and the value 982 for the gravity acceleration, the pressure p at the depth d metres must be $p = \frac{0{\cdot}982}{0{\cdot}973}\, d = 1{\cdot}01\ d$ decibars. Thus the differences $\alpha_{S'',t'',p} - \alpha_{S',t',p}$ and $\alpha_{S'',t'',d} - \alpha_{S',t',d}$ may be considered equal, the differences between the pressures p and d decibars being less than one per cent.

In the calculation of the differences $\alpha_{S'',t'',p} - \alpha_{S',t',p}$ two different procedures were employed, some calculations were made by both methods for the sake of control.

Procedure I. According to V. Bjerknes the specific volume $\alpha_{S,t,p}$ may be written as:

$$\alpha_{S,t,p} = \alpha_{35,0,p} + \delta_S + \delta_t + \delta_{S,t} + \delta_{S,p} + \delta_{t,p} + \delta_{S,t,p} \qquad (1)$$

According to H. U. Sverdrup[2]) we designate the value of $\delta_S + \delta_t + \delta_{S,t}$ in (1) by $\Delta_{S,t}$. The difference between the specific volumes at the

[1]) V. Bjerknes. Dynamic Meteorology and Hydrography. Washington, D. C., 1910.

[2]) H. U. Sverdrup. Vereinfachtes Verfahren zur Berechnung der Druck- und Massenverteilung im Meere. Geofysiske Publikasjoner, Vol. X, No. 1, Oslo 1935.

stations H″ and H′ at an isobaric surface where the pressure is p, may thus be written:

$$\alpha_{S'',t'',p} - \alpha_{S',t',p} = (\Delta_{S'',t''} - \Delta_{S',t'}) + (\delta_{t'',p} - \delta_{t',p}) + (\delta_{S''p} - \delta_{S',p}) + (\delta_{S'',t'',p} - \delta_{S',t',p}) \quad (2)$$

In (2) the difference $\delta_{S'',t'',p} - \delta_{S',t',p}$ may always be disregarded and so may the difference $\delta_{S'',p} - \delta_{S',p}$ for the area of the Faroe—Shetland Channel. Thus expression (2) may be written.

$$\alpha_{S'',t'',p} - \alpha_{S',t',p} = [(0{\cdot}97264 + \Delta_{S'',t''}) + \delta_{t'',p}] - [(0{\cdot}97264 + \Delta_{S't'}) + \delta_{t',p}] \quad (3)$$

where 0·97264 is the value of $\alpha_{35,0,0}$.

The values of $[(0{\cdot}97264 + \Delta_{S,t}) + \delta_{t,p}]$ were calculated for the series of observations at the stations considered, using for p the figures indicating the observed depths in metres. The values of $0{\cdot}97264 + \Delta_{S,t}$ were usually found by means of the Oscar Sund[1]) slide rule, but the tables prepared by J. W. Sandström and B. Helland-Hansen[2]) were also used occasionally. The values of $\delta_{t,p}$ were found by means of a diagram prepared on the basis of H. U. Sverdrup's[3]) tables. Afterwards the differences $\alpha_{S'',t'',p} - \alpha_{S',t',p}$ were computed for the different pairs of stations used in the further calculations.

Procedure II. Tab. 11 has been constructed for direct calculation of the differences $\alpha_{S'',t'',p} - \alpha_{S',t',p}$ according to the expression:

$$10^5 (\alpha_{S'',t'',p} - \alpha_{S',t',p}) = k_{S''-S'} (S'' - S') + (k_{t''-t'} + \Delta k_{t''-t'}) (t'' - t') \quad (4)$$

the coefficients $k_{S''-S'}$ and $k_{t''-t'} + \Delta k_{t''-t'}$ being determined by the table. Values of $k_{S''-S'}$ and $k_{t''-t'}$ are tabulated for values $\frac{t'' + t'}{2}$ and p and further values of $\Delta k_{t''-t'}$ are tabulated in the auxiliary table below the main table for values of $\frac{S'' + S'}{2}$. Interpolation tables, to be used at the computation of $k_{t''-t'}$ and $k_{S''-S'}$ for a given value of $\frac{t'' + t'}{2}$, are given in addition to the main table. An example of the use of the table is given below the main table.

The table covers the intervals from 33 ‰ to 36 ‰ of salinity, from —1° to +13° of temperature and from 0 to 1500 decibars of sea water pressure. Within these intervals it is possible to calculate a difference 10^5 $(\alpha_{S'',t'',p} - \alpha_{S',t',p})$ with a margin hardly exceeding a unit even for the greatest values of the differences $S'' - S'$ and $t'' - t'$.

It is of importance to note that the exactness of a calculated difference: $10^5 (\alpha_{S'',t'',p} - \alpha_{S',t',p})$ *will be great when the differences* $S'' - S'$ and $t'' - t'$ *are small.* The fact that the influence of each of the differences $S'' - S'$ and $t'' - t'$ on the difference between the specific volumes is found separately may also in some cases be an advantage.

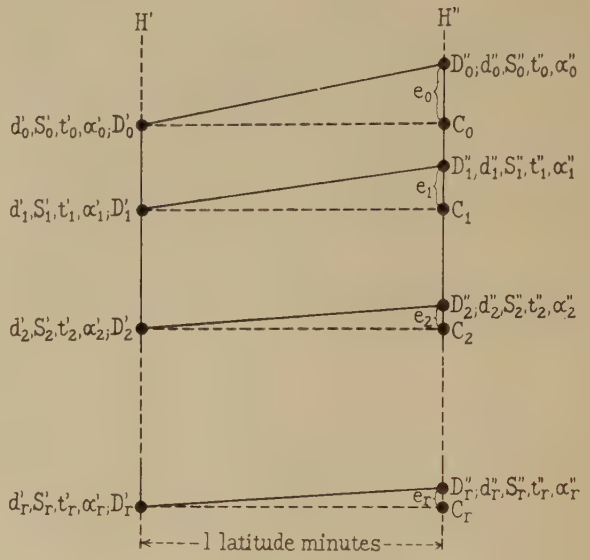


Fig. 24.

Calculations based on the actual Intervals of Depth.

The calculations were carried out subject to the usual suppositions, i.e., that the movements of the water are considered stationary during the time used for the observations in a section, and that the internal friction is considered nil. The details of the procedure are explained below.

In Fig. 24 two stations H′ and H″ are represented by their verticals. The distance between the stations is l latitudinal minutes. Points D'_0, D'_1, D'_2 .... D'_r and D''_0, D''_1, D''_2 .... D''_r are marked on the verticals. The sea water pressure is presumed to be the same at two points D′ and D″ marked with the same index. The isobaric surfaces represented by the lines $D'_0\,D''_0$, $D'_1\,D''_1$, ... $D'_r\,D''_r$ are called the 0, the 1st, the 2nd ... and the rth isobaric surface. The 0 isobaric surface is supposed to be the surface of the sea. The distance from the surface of the sea, the salinity, the temperature and the specific volume at a point D are designated by d, S, t and α with the same mark and

[1]) Oscar Sund. An Oceanographical Slide Rule. Journ. du Conseil, Vol. IV, p. 93, Copenhague, 1929.

[2]) J. W. Sandström und B. Helland-Hansen. Über die Berechnung von Meeresströmungen. Rep. Norw. Fish. and Mar. Invest., Vol. II, No. 4, Bergen, 1903.

[3]) H. U. Sverdrup. l. c.

Table 11. Calculation of Differences between Specific Volumes of Sea Water.

$10^5\,(\alpha_{S'',t'',p} - \alpha_{S',t',p}) \quad k_{S''-S'}\,(S'' - S') + (k_{t''-t'} + \Delta k_{t''-t'})\,(t'' - t').$

p Decibar	$\frac{t''+t'}{2}$ →	−1	0	1	2	3	4	5	6	7	8	9	10	11	12	13
0	$k_{S''-S'}$	—76·5	—76·2	—76·0	—75·8	—75·5	—75·3	—75·0	—74·8	—74·6	—74·3	—74·1	—73·8	—73·6	—73·4	—73·1
	$k_{t''-t'}$	4·4	5·4	6·5	7·6	8·7	9·8	10·9	12·0	13·1	14·2	15.3	16·4	17·4	18·5	19·6
10	$k_{S''-S'}$	—76·5	—76·2	—76·0	—75·8	—75·5	—75·3	—75·0	—74·8	—74·6	—74·3	—74·1	—73·8	—73·6	—73·4	—73·1
	$k_{t''-t'}$	4·4	5·5	6·6	7·7	8·7	9·8	10·9	12·0	13·1	14·2	15.3	16·4	17·5	18·5	19·6
20	$k_{S''-S'}$	—76·5	—76·2	—76·0	—75·7	—75·5	—75·3	—75·0	—74·8	—74·5	—74·3	—74·1	—73·8	—73·6	—73·3	—73·1
	$k_{t''-t'}$	4·4	5·5	6·6	7·7	8·8	9·9	10·9	12·0	13·1	14·2	15.3	16·4	17·5	18·6	19·7
30	$k_{S''-S'}$	—76·4	—76·2	—76·0	—75·7	—75·5	—75·2	—75·0	—74·8	—74·5	—74·3	—74·0	—73·8	—73·6	—73·3	—73·1
	$k_{t''-t'}$	4·4	5·5	6·6	7·7	8·8	9·9	11·0	12·1	13·1	14·2	15.3	16·4	17·5	18·6	19·7
40	$k_{S''-S'}$	—76·4	—76·2	—76·0	—75·7	—75·5	—75·2	—75·0	—74·8	—74·5	—74·3	—74·0	—73·8	—73·6	—73·3	—73·1
	$k_{t''-t'}$	4·5	5·6	6·6	7·7	8·8	9·9	11·0	12·1	13·2	14·2	15.3	16·4	17·5	18·6	19·7
50	$k_{S''-S'}$	—76·4	—76·2	—75·9	—75·7	—75·4	—75·2	—75·0	—74·7	—74·5	—74·2	—74·0	—73·8	—73·5	—73·3	—73·0
	$k_{t''-t'}$	4·5	5·6	6·7	7·8	8·8	9·9	11·0	12·1	13·2	14·3	15.4	16·4	17·5	18·6	19·7
60	$k_{S''-S'}$	—76·4	—76·2	—75·9	—75·7	—75·4	—75·2	—75·0	—74·7	—74·5	—74·2	—74·0	—73·8	—73·5	—73·3	—73·0
	$k_{t''-t'}$	4·5	5·6	6·7	7·8	8·9	9·9	11·0	12·1	13·2	14·3	15.4	16·5	17·5	18·6	19·7
70	$k_{S''-S'}$	—76·4	—76·2	—75·9	—75·7	—75·4	—75·2	—75·0	—74·7	—74·5	—74·2	—74·0	—73·8	—73·5	—73·3	—73·0
	$k_{t''-t'}$	4·6	5·6	6·7	7·8	8·9	10·0	11·1	12·1	13·2	14·3	15.4	16·5	17·6	18·6	19·7
80	$k_{S''-S'}$	—76·4	—76·1	—75·9	—75·6	—75·4	—75·2	—74·9	—74·7	—74·4	—74·2	—74·0	—73·7	—73·5	—73·2	—73·0
	$k_{t''-t'}$	4·6	5·7	6·7	7·8	8·9	10·0	11·1	12·2	13·2	14·3	15.4	16·5	17·6	18·7	19·7
90	$k_{S''-S'}$	—76·4	—76·1	—75·9	—75·6	—75·4	—75·2	—74·9	—74·7	—74·4	—74·2	—74·0	—73·7	—73·5	—73·2	—73·0
	$k_{t''-t'}$	4·6	5·7	6·8	7·9	8·9	10·0	11·1	12·2	13·3	14·3	15.4	16·5	17·6	18·7	19·8
100	$k_{S''-S'}$	—76·3	—76·1	—75·9	—75·6	—75·4	—75·1	—74·9	—74·7	—74·4	—74·2	—73·9	—73·7	—73·5	—73·2	—73·0
	$k_{t''-t'}$	4·6	5·7	6·8	7·9	9·0	10·0	11·1	12·2	13·3	14·4	15.4	16·5	17·6	18·7	19·8
125	$k_{S''-S'}$	—76·3	—76·1	—75·8	—75·6	—75·3	—75·1	—74·9	—74·6	—74·4	—74·1	—73·9	—73·7	—73·4	—73·2	—72·9
	$k_{t''-t'}$	4·7	5·8	6·9	7·9	9·0	10·1	11·2	12·3	13·3	14·4	15.5	16·6	17·7	18·7	19·8
150	$k_{S''-S'}$	—76·3	—76·0	—75·8	—75·6	—75·3	—75·1	—74·8	—74·6	—74·4	—74·1	—73·9	—73·6	—73·4	—73·2	—72·9
	$k_{t''-t'}$	4·8	5·8	6·9	8·0	9·1	10·2	11·2	12·3	13·4	14·5	15.5	16·6	17·7	18·8	19·9
200	$k_{S''-S'}$	—76·2	—76·0	—75·7	—75·5	—75·2	—75·0	—74·8	—74·5	—74·3	—74·0	—73·8	—73·6	—73·3	—73·1	—72·8
	$k_{t''-t'}$	4·9	6·0	7·1	8·1	9·2	10·3	11·3	12·4	13·5	14·6	15.6	16·7	17·8	18·9	19·9
250	$k_{S''-S'}$	—76·1	—75·9	—75·6	—75·4	—75·2	—74·9	—74·7	—74·4	—74·2	—74·0	—73·7	—73·5	—73·2	—73·0	—72·8
	$k_{t''-t'}$	5·0	6·1	7·2	8·2	9·3	10·4	11·5	12·5	13·6	14·7	15.7	16·8	17·9	18·9	20·0
300	$k_{S''-S'}$	—76·0	—75·8	—75·6	—75·3	—75·1	—74·8	—74·6	—74·4	—74·1	—73·9	—73·6	—73·4	—73·2	—72·9	—72·7
	$k_{t''-t'}$	5·2	6·2	7·3	8·4	9·4	10·5	11·6	12·6	13·7	14·8	15.8	16·9	18·0	19·0	20·1
350	$k_{S''-S'}$	—76·0	—75·7	—75·5	—75·2	—75·0	—74·8	—74·5	—74·3	—74·0	—73·8	—73·6	—73·3	—73·1	—72·8	—72·6
	$k_{t''-t'}$	5·3	6·4	7·4	8·5	9·6	10·6	11·7	12·7	13·8	14·9	15.9	17·0	18·0	19·1	20·2
400	$k_{S''-S'}$	—75·9	—75·6	—75·4	—75·2	—74·9	—74·7	—74·4	—74·2	—74·0	—73·7	—73·5	—73·2	—73·0	—72·8	—72·5
	$k_{t''-t'}$	5·4	6·5	7·6	8·6	9·7	10·7	11·8	12·8	13·9	15·0	16.0	17·1	18·1	19·2	20·2

$\frac{S''+S'}{2}$	33·1	33·5	34·0	34·4	34·8	35·2	35·6	36·0
$\Delta k_{t''-t'}$	—0·4	—0·3	—0·2	—0·1	0·0	0·1	0·2	

p Decibar	$\frac{t''+t'}{2}$ →	−1	0	1	2	3	4	5	6	7	8	9	10	11	12	13
400	$k_{S''-S'}$	−75·9	−75·6	−75·4	−75·2	−74·9	−74·7	−74·4	−74·2	−74·0	−73·7	−73·5	−73·2	−73·0	−72·8	−72·5
	$k_{t''-t'}$	5·4	6·5	7·6	8·6	9·7	10·7	11·8	12·8	13·9	15·0	16·0	17·1	18·1	19·2	20·2
450	$k_{S''-S'}$	−75·8	−75·6	−75·3	−75·1	−74·8	−74·6	−74·4	−74·1	−73·9	−73·6	−73·4	−73·2	−72·9	−72·7	−72·4
	$k_{t''-t'}$	5·6	6·6	7·7	8·7	9·8	10·8	11·9	12·9	14·0	15·0	16·1	17·2	18·2	19·3	20·3
500	$k_{S''-S'}$	−75·7	−75·5	−75·3	−75·0	−74·8	−74·5	−74·3	−74·1	−73·8	−73·6	−73·3	−73·1	−72·9	−72·6	−72·4
	$k_{t''-t'}$	5·7	6·8	7·8	8·9	9·9	11·0	12·0	13·0	14·1	15·1	16·2	17·2	18·3	19·3	20·4
550	$k_{S''-S'}$	−75·7	−75·4	−75·2	−75·0	−74·7	−74·5	−74·2	−74·0	−73·8	−73·5	−73·3	−73·0	−72·8	−72·6	−72·3
	$k_{t''-t'}$	5·8	6·9	7·9	9·0	10·0	11·1	12·1	13·1	14·2	15·2	16·3	17·3	18·4	19·4	20·5
600	$k_{S''-S'}$	−75·6	−75·4	−75·1	−74·9	−74·6	−74·4	−74·2	−73·9	−73·7	−73·4	−73·2	−73·0	−72·7	−72·5	−72·2
	$k_{t''-t'}$	6·0	7·0	8·1	9·1	10·1	11·2	12·2	13·3	14·3	15·3	16·4	17·4	18·5	19·5	20·5
650	$k_{S''-S'}$	−75·5	−75·3	−75·0	−74·8	−74·6	−74·3	−74·1	−73·8	−73·6	−73·4	−73·1	−72·9	−72·6	−72·4	−72·2
	$k_{t''-t'}$	6·1	7·1	8·2	9·2	10·2	11·3	12·3	13·4	14·4	15·4	16·5	17·5	18·5	19·6	20·6
700	$k_{S''-S'}$	−75·4	−75·2	−75·0	−74·7	−74·5	−74·2	−74·0	−73·8	−73·5	−73·3	−73·0	−72·8	−72·6	−72·3	−72·1
	$k_{t''-t'}$	6·2	7·3	8·3	9·3	10·4	11·4	12·4	13·5	14·5	15·5	16·6	17·6	18·6	19·6	20·7
750	$k_{S''-S'}$	−75·4	−75·1	−74·9	−74·6	−74·4	−74·2	−73·9	−73·7	−73·4	−73·2	−73·0	−72·7	−72·5	−72·2	−72·0
	$k_{t''-t'}$	6·4	7·4	8·4	9·5	10·5	11·5	12·5	13·6	14·6	15·6	16·6	17·7	18·7	19·7	20·7
800	$k_{S''-S'}$	−75·3	−75·0	−74·8	−74·6	−74·3	−74·1	−73·8	−73·6	−73·4	−73·1	−72·9	−72·6	−72·4	−72·2	−71·9
	$k_{t''-t'}$	6·5	7·5	8·5	9·6	10·6	11·6	12·6	13·7	14·7	15·7	16·7	17·8	18·8	19·8	20·8
850	$k_{S''-S'}$	−75·2	−75·0	−74·7	−74·5	−74·2	−74·0	−73·8	−73·5	−73·3	−73·0	−72·8	−72·6	−72·3	−72·1	−71·8
	$k_{t''-t'}$	6·6	7·7	8·7	9·7	10·7	11·7	12·7	13·8	14·8	15·8	16·8	17·8	18·9	19·9	20·9
900	$k_{S''-S'}$	−75·1	−74·9	−74·7	−74·4	−74·2	−73·9	−73·7	−73·5	−73·2	−73·0	−72·7	−72·5	−72·3	−72·0	−71·8
	$k_{t''-t'}$	6·8	7·8	8·8	9·8	10·8	11·8	12·8	13·9	14·9	15·9	16·9	17·9	18·9	20·0	21·0
950	$k_{S''-S'}$	−75·1	−74·8	−74·6	−74·4	−74·1	−73·9	−73·6	−73·4	−73·2	−72·9	−72·7	−72·4	−72·2	−72·0	−71·7
	$k_{t''-t'}$	6·9	7·9	8·9	9·9	10·9	11·9	13·0	14·0	15·0	16·0	17·0	18·0	19·0	20·0	21·0
1000	$k_{S''-S'}$	−75·0	−74·8	−74·5	−74·3	−74·0	−73·8	−73·6	−73·3	−73·1	−72·8	−72·6	−72·4	−72·1	−71·9	−71·6
	$k_{t''-t'}$	7·0	8·0	9·0	10·0	11·0	12·1	13·1	14·1	15·1	16·1	17·1	18·1	19·1	20·1	21·1
1100	$k_{S''-S'}$	−74·8	−74·6	−74·4	−74·1	−73·9	−73·6	−73·4	−73·2	−72·9	−72·7	−72·4	−72·2	−72·0	−71·7	−71·5
	$k_{t''-t'}$	7·3	8·3	9·3	10·3	11·3	12·3	13·3	14·3	15·3	16·3	17·3	18·3	19·3	20·3	21·2
1200	$k_{S''-S'}$	−74·7	−74·4	−74·2	−74·0	−73·7	−73·5	−73·2	−73·0	−72·8	−72·5	−72·3	−72·0	−71·8	−71·6	−71·3
	$k_{t''-t'}$	7·5	8·5	9·5	10·5	11·5	12·5	13·5	14·5	15·5	16·4	17·4	18·4	19·4	20·4	21·4
1300	$k_{S''-S'}$	−74·5	−74·3	−74·1	−73·8	−73·6	−73·3	−73·1	−72·9	−72·6	−72·4	−72·1	−71·9	−71·7	−71·4	−71·2
	$k_{t''-t'}$	7·8	8·8	9·8	10·7	11·7	12·7	13·7	14·7	15·6	16·6	17·6	18·6	19·6	20·5	21·5
1400	$k_{S''-S'}$	−74·4	−74·2	−73·9	−73·7	−73·4	−73·2	−73·0	−72·7	−72·5	−72·2	−72·0	−71·8	−71·5	−71·3	−71·0
	$k_{t''-t'}$	8·1	9·0	10·0	11·0	11·9	12·9	13·9	14·9	15·8	16·8	17·8	18·7	19·7	20·7	21·7
1500	$k_{S''-S'}$	−74·2	−74·0	−73·8	−73·5	−73·3	−73·0	−72·8	−72·6	−72·3	−72·1	−71·8	−71·6	−71·4	−71·1	−70·9
	$k_{t''-t'}$	8·3	9·3	10·2	11·2	12·2	13·1	14·1	15·1	16·0	17·0	17·9	18·9	19·9	20·8	21·8

Example. At the depth 400 m. at the Stations H′ and H″ was found $t' = 6{\cdot}24°$, $S' = 35{\cdot}28\ ‰$ and $t'' = 7{\cdot}95°$, $S'' = 35{\cdot}35\ ‰$. The observed values of temperature and salinity are regarded as valid for the water pressure 400 decibars. We have: $S'' - S' = 0{\cdot}07$; $t'' - t' = 1{\cdot}71°$; $\frac{S''+S'}{2} = 35{\cdot}32$; $\frac{t''+t'}{2} = 7{\cdot}10$. From the auxiliary table is found $\Delta k_{t''-t'} = 0{\cdot}1$ and from the main table $k_{S''-S'} = -74{\cdot}0$ and $k_{t''-t'} = 14{\cdot}0$. One gets: $10^5\ (\alpha_{S'',t'',p} - \alpha_{S',t',p}) = -74.0 \cdot 0.07 + (14.0 + 0.1) \cdot 1.71 = 18{\cdot}9$

index as the relevant point D. The lines $D'_0\ C_0$, $D'_1\ C_1$, $D'_2\ C_2$ .... $D'_r\ C_r$ represent the equipotential surfaces through the points D'_0, D'_1 ... D'_r. The distances $C_0\ D''_0$, $C_1\ D''_1$ .... $C_r\ D''_r$, situated on the vertical H″, are the elevations of the isobaric surfaces from station H′ to station H″. These elevations are called e_0, e_1 .... e_r.

We presume the specific volumes α at the depths d are known and the depth intervals so small that the variation of the specific volume within an interval may be considered linear. Two successive isobaric surfaces, arbitrarily chosen, are called the x^{th} and the $(x+1)^{\text{st}}$ isobaric surface. Symbols referring to these surfaces are marked with the indices x and $x+1$. The mean values of the gravity acceleration at stations H′ and H″ between the x^{th} and the $(x+1)^{\text{st}}$ surface are designated by g' and g''. Thus, we get with sufficient approximation that:

$$e_x - e_{x+1} = 10^{-3}\,(d'_{x+1} - d'_x)\cdot \frac{10^5\,(\alpha''_x - \alpha'_x) + 10^5\,(\alpha''_{x+1} - \alpha'_{x+1})}{\alpha'_x + \alpha'_{x+1}} \cdot \frac{g'}{g''} \qquad (5)$$

By using (5) on the material from the Faroe—Shetland Channel area we may reckon $\alpha'_x + \alpha'_{x+1}$ as being equal to $2 \cdot 0{\cdot}973$ ml./g. and $g' : g''$ as being equal to 1, without introducing any appreciable error into the calculations. For an arbitrary isobaric surface we put:

$$10^5\,(\alpha'' - \alpha') = \Delta \qquad (6)$$

and thus (5) may be written:

$$e_x - e_{x+1} = 0{\cdot}514 \cdot 10^{-3}(d'_{x+1} - d'_x)\cdot (\Delta_x + \Delta_{x+1}) \qquad (7)$$

where the depth difference $d'_{x+1} - d'_x$ is expressed in metres and the elevation difference $e_x - e_{x+1}$ in centimetres.

Referring to the x^{th} and the $(x+1)^{\text{st}}$ isobaric surface we put

$$10^{-3}\,(d'_{x+1} - d'_x)\,(\Delta_x + \Delta_{x+1}) = a_{x,x+1} \qquad (8)$$

and thus (7) may be written:

$$e_x - e_{x+1} = 0{\cdot}514 \cdot a_{x,x+1} \qquad (9)$$

By summation of the elevation differences $e_x - e_{x+1}$ between the n^{th} and the r^{th} isobaric surface we get:

$$e_n - e_r = 0{\cdot}514 \sum_{x=n}^{x=r-1} a_{x,x+1} \qquad (10)$$

The r^{th} isobaric surface may be chosen as a reference-surface. Thus the difference $e_n - e_r$ between the elevation of an arbitrary isobaric surface — i.e., the n^{th} isobaric surface — and the elevation of the reference-surface may be found by means of (8) and (10). The expression $\sum_{x=n}^{x=r-1} a_{x,x+1}$ in (10) for n equal to 0, 1, 2 ... $r-1$ is found by successive additions, as shown below in (11)

$$\left.\begin{aligned}
&\sum_{x=r-1}^{x=r-1} a_{x,x+1} = 10^{-3}\,(d'_r - d'_{r-1})\,(\Delta_r + \Delta_{r-1})\\
&\sum_{x=r-2}^{x=r-1} a_{x,x+1} = 10^{-3}\,(d'_{r-1} - d'_{r-2})\cdot (\Delta_{r-1} + \Delta_{r-2}) + \sum_{x=r-1}^{x=r-1} a_{x,x+1}\\
&\sum_{x=r-3}^{x=r-1} a_{x,x+1} = 10^{-3}\,(d'_{r-2} - d'_{r-3})\cdot (\Delta_{r-2} + \Delta_{r-3}) + \sum_{x=r-2}^{x=r-1} a_{x,x+1}\\
&\quad\vdots\\
&\sum_{x=1}^{x=r-1} a_{x,x+1} = 10^{-3}\,(d'_2 - d'_1)\cdot (\Delta_2 - \Delta_1) + \sum_{x=2}^{x=r-1} a_{x,x+1}\\
&\sum_{x=0}^{x=r-1} a_{x,x+1} = 10^{-3}\,(d'_1 - d'_0)\cdot (\Delta_1 + \Delta_0) + \sum_{x=1}^{x=r-1} a_{x,x+1}
\end{aligned}\right\} \qquad (11)$$

The elevation differences $e_{r-1} - e_r$, $e_{r-2} - e_r$, $e_{r-3} - e_r$ ... $e_1 - e_r$ and $e_0 - e_r$ may be found in centimetres by multiplying the values of the left side expressions in (11) with 0·514.

For the latitude φ we will call the length of a latitudinal minute given in centimetres s. The distance between stations H′ and H″ which is l latitudinal minutes will then be ls centimetres. Subject to the assumptions already mentioned — stationary, frictionless movements of the water — the mean value v_n for the current at right angles to the section at the n^{th} isobaric surface with the elevation e_n may be expressed by

$$v_n = \frac{g}{2sl\,\omega \sin\varphi} \cdot e_n \qquad (12)$$

where $\omega = 0{\cdot}00007292$ is the angular velocity of the earth and g the gravity acceleration measured in cm./sec^2. On the northern hemisphere the direction of the current v_n deviates 90° to the right in relation to the sloping direction of the isobaric surface. We put:

$$\frac{1}{2\,\omega \sin\varphi} = c \qquad (13)$$

and thus we have:

$$v_n = \frac{cg}{sl} \cdot e_n \qquad (14)$$

and by analogy

$$v_r = \frac{cg}{sl} \cdot e_r \qquad (15)$$

From (10), (14) and (15) we get:

$$v_n = 0{\cdot}514 \frac{cg}{sl} \sum_{x=n}^{x=r-1} a_{x,x+1} + v_r \qquad (16)$$

The mean value of currents through an area between stations H′ and H″ and between the n^{th} and $(n+1)^{st}$ isobaric surface is called $v_{n,n+1}$ and considered equal to the mean of the currents v_n and v_{n+1}. Thus we have:

$$v_{n,n+1} = 0{\cdot}257 \frac{cg}{sl} \left(\sum_{x=n}^{x=r-1} a_{x,x+1} + \sum_{x=n+1}^{x=r-1} a_{x,x+1} \right) + v_r \qquad (17)$$

The intensity of the flow measured in km.^{3}/hour through the above-stated area is called $q_{n,n+1}$. By means of (17) we get:

$$\left. \begin{aligned} q_{n,n+1} = 0{\cdot}925 \cdot 10^{-10} \cdot cg \ (d'_{n+1} - d'_n) \cdot \\ \left(\sum_{x=n}^{x=r-1} a_{x,x+1} + \sum_{x=n+1}^{x=r-1} a_{x,x+1} \right) + 3{\cdot}6 \cdot 10^{-10} \cdot \\ (d'_{n+1} - d'_n) \ sl v_r \end{aligned} \right\} \qquad (18)$$

The intensity of the flow — measured in km.^{3}/hour — through the area between stations H′ and H″ and below the reference-surface is called m. The intensity Q of the flow through the whole interval between stations H′ and H″ may then be expressed by:

$$\left. \begin{aligned} Q = 0{\cdot}925 \cdot 10^{-10} \ cg \sum_{n=0}^{n=r-1} (d'_{n+1} - d'_n) \cdot \\ \left(\sum_{x=n}^{x=r-1} a_{x,x+1} + \sum_{x=n+1}^{x=r-1} a_{x,x+1} \right) \\ + 3{\cdot}6 \cdot 10^{-10} \ sl \ d_r \ v_r + m \end{aligned} \right\} \qquad (19)$$

Expressions (17), (18) and (19) were used in connection with a reference-surface, which for each pair of stations was chosen at or near the bottom at the station with the lesser depth. The chosen reference-surface could then, in many cases, be taken to coincide with an equipotential surface, i.e., it could be considered a zero-surface. In these cases the value af v_r in expressions (17), (18) and (19) must be put equal to nought. Furthermore, the intensity m of the flow through the area between the stations and below the reference-surface could also in such cases be put equal to nought. Under these circumstances the above expressions (17), (18) and (19) are reduced on their right-hand side to contain the first term only.

In several cases, however, the chosen reference-surface could not be considered a zero-surface. Nevertheless, the calculations were carried out as if the chosen reference-surface were a zero-surface, thus rendering necessary a subsequent correction of the results. The calculation of the corrections and the consequent amendments of the results obtained are dealt with below (see p. 40).

Expressions (17), (18) and (19) contain the constants $0{\cdot}257 \ cg : s$ and $0{\cdot}925 \cdot 10^{-10} \ cg$. Values of these constants for latitudes from 57° to 63° are given in Tab. 12.

Tab. 13 records an example of the calculation of the current and the intensity of the flow through intervals of depth between two stations H′ and H″ and of the calculation of the intensity of the flow through the whole interval between the stations. The situation of the stations and the time of the observations are stated at the head of the table. The isobaric surface at the depth 1180 metres has been regarded as a zero-surface. Currents below that surface have been disregarded. The computations have been carried out in accordance with expressions (17), (18) and (19). The constants in these expressions are found from Tab. 12 and are stated at the head of Tab. 13. The computation of the differences in the specific volumes has been made by means of Tab. 11.

Calculations based on Equal Intervals.

The calculations in the preceding chapter are based on the actual intervals of depth. In these calculations the variation of the difference between the specific volumes at the same depth at two stations H′ and H″ has been taken to vary linearly with the depth within each of the intervals. The variation with the depth of this difference might in many cases be found with relatively good accuracy by graphical interpolation in connection

Table 12.

Latitude	g	c	$10^{-6} \ cg$	$10^{-2} \ s$	$0{\cdot}257 \frac{cg}{s}$	$0{\cdot}925 \ 10^{-10} \ cg$
57°	981·7	8176	8·026	1856	11·11	0·000742
58°	981·8	8085	7·938	1856	10·99	0.000734
59°	981·8	7999	7·854	1857	10·87	0·000727
60°	981·9	7918	7·774	1857	10·76	0·000719
61°	982·0	7840	7·699	1857	10·65	0·000712
62°	982·1	7766	7·627	1858	10·55	0·000705
63°	982·1	7696	7·558	1858	10·46	0·000699

Table 13.

H′ : φ' = 61°27′N., λ' = 3°42′W.; depth 1250m.; 1906, VI·15; $\frac{\varphi' + \varphi''}{2}$ = 61°22·5′; l = 22·5

H″ : φ'' 61°18′N., λ'' = 2°59′W.; depth 1180m.; 1906, VI·15; 0·257 $\frac{cg}{sl}$ = 0·472; $0{\cdot}925 \cdot 10^{-10}\, cg = 0{\cdot}000709$

Isobaric surface No.	Depth Metres	$\frac{S''+S'}{2}$	$\frac{t''+t'}{2}$	$S''-S'$	$t''-t'$	$k_{S''-S'} \times (S''-S')$	$(k_{t''-t'} + \Delta k_{t''-t'}) \times (t''-t')$	$10^5 \times (\alpha_{S'',t'',p} - \alpha_{S',t',p})$	$a_{x,x+1}$	$\sum_{x=n}^{x=23} a_{x,x+1}$	$\sum_{x=n}^{x=23} a_{x,x+1} + \sum_{x=n+1}^{x=23} a_{x,x-1}$	$v_{n,n+1}$ cm. sec.	$q_{n,n+1}$ km.³/hour
0	0	35·22	8·65	0·07	0·20	—5·2	3·0	—2	—0·05	16·60	33·2	15·7	0·24
1	10	·22	8·57	0·09	0·26	—6·7	3·9	—3	0·01	16·65	33·3	15·7	0·24
2	20	·20	7·92	0·12	0·93	—8·9	13·1	4	0·10	16·64	33·2	15·7	0·24
3	30	·18	7·12	0·16	1·35	—11·9	17·8	6	0·08	16·54	33·0	15·6	0·23
4	40	·16	6·91	0·13	0·93	—9·7	12·2	2	0·28	16·46	32·6	15·4	0·46
5	60	·14	6·31	0·13	1·74	—9·7	21·6	12	0·58	16·18	31·8	15·0	0·45
6	80	·13	5·79	0·12	2·20	—9·0	26·4	17	0·68	15·60	30·5	14·4	0·43
7	100	·12	5·63	0·14	2·32	—10·5	27·4	17	1·95	14·92	27·9	13·2	0·99
8	150	·08	5·10	0·18	3·10	—13·5	35·0	22	2·40	12·97	23·5	11·1	0·83
9	200	·06	4·19	0·20	3·91	—15·0	41·1	26	2·60	10·57	18·5	8·7	0·66
10	250	·02	3·78	0·20	4·03	—15·0	41·1	26	2·30	7·97	13·6	6·4	0·48
11	300	34·98	3·00	0·13	3·15	—9·8	29·6	20	1·90	5·67	9·4	4·4	0·33
12	350	·96	2·19	0·07	2·72	—5·3	23·7	18	1·70	3·77	5·8	2·7	0·21
13	400	·93	1·44	0·02	2·20	—1·5	17·6	16	1·13	2·07	3·0	1·4	0·11
14	450	·92	0·56	0·00	0·92	0·0	6·6	6·6	0·46	0·94	1·4	0·7	0·05
15	500	·92	0·12	0·00	0·37	0·0	2·6	2·6	0·16	0·48	0·8	0·4	0·03
16	550	·92	—0·14	0·00	0·11	0·0	0·7	0·7	0·06	0·32	0·6	0·3	0·02
17	600	·92	—0·30	0·00	0·09	0·0	0·6	0·6	0·11	0·26	0·4	0·2	0·03
18	700	·92[1]	—0·46[1]	0·00[1]	0·07[1]	0·0	0·5	0·5	0·07	0·15	0·2	0·1	0·01
19	800	·92	—0·58	0·00	0·03	0·0	0·2	0·2	0·03	0·08	0·1	0·0	0·01
20	900	·92[1]	—0·66[1]	0·00[1]	0·01[1]	0·0	0·1	0·1	0·02	0·05	0·1	0·0	0·01
21	1000	·92[1]	—0·76[1]	0·00[1]	0·01[1]	0·0	0·1	0·1	0·03	0·03	0·0	0·0	0·00
22	1100	·92[1]	—0·85[1]	0·00[1]	0·02[1]	0·0	0·2	0·2	0·00	0·00	0·0	0·0	0·00
23	1180	·92[1]	—0·90[1]	0·00[1]	—0·02[1]	0·0	—0·2	—0·2	0·00	0·00			Q = 6·06

1) The values of S and t at one of the stations have been interpolated from values in neighbouring depths.
2) The isobaric surface at the depth 1180 m. has been used as a reference-surface and is regarded as a zero-surface.

with a smoothing of the actual differences. Instead of such direct interpolation, however, the method described below was used.

TS-curves based on the observed values of salinity and temperature at the different depths at stations H′ and H″ were constructed for each of the stations. A slight smoothing was applied in

The observations at Stations H′ and H″ used in the calculation of Tab. 13 are plotted in Figs. 25a and b. The smoothed TS-curves for the two stations are identical for salinities and temperatures lower than 35·05 ‰ and 4·6° respectively, but the indications of depths, given in hectometres, for waters of the same qualities are different. The depth of

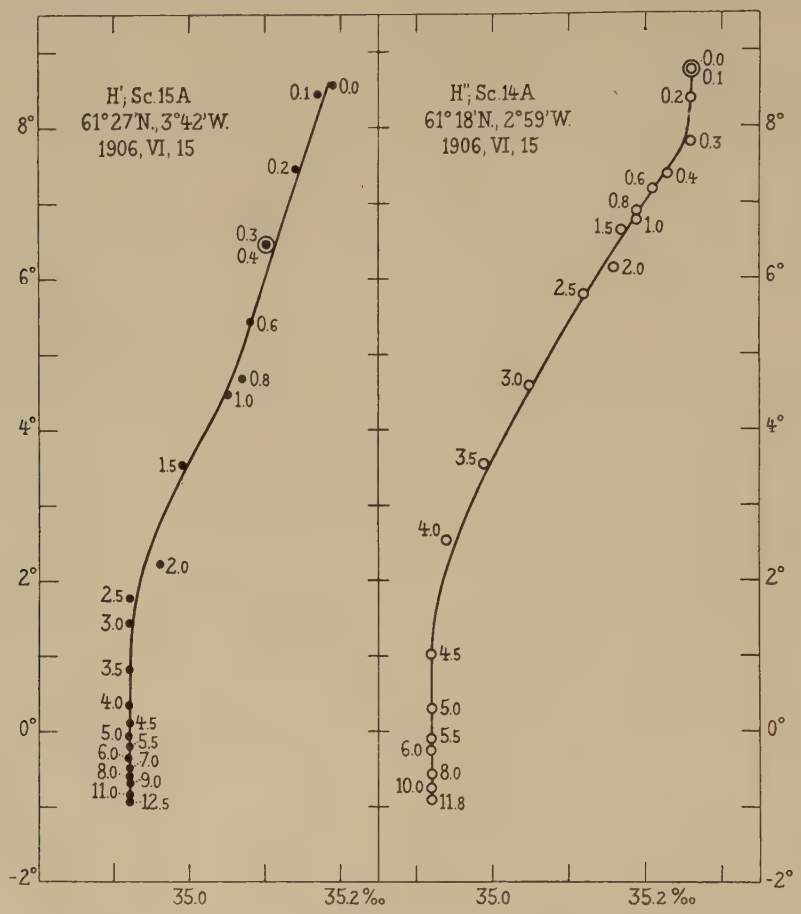


Fig. 25. a. b.

the construction of the curves. The smoothed values for S and T were read from the curves for the depths at which the observations had been taken and were used for the computation of the terms $k_{S''-S'}$ $(S'' - S')$ and $(k_{t''-t'} + \Delta k_{t''-t'})$ $(t'' - t')$ according to (4) by means of Tab. 11. The computed terms were plotted graphically and slightly smoothed curves drawn to show the variation of the terms with the depth. By means of these curves the differences between the specific volumes at the same depth at Stations H′ and H″ could be determined for a selected series of depths with equal intervals. Details of the procedure are illustrated by means of the following example derived from the same material as was used for the example in the preceding chapter.

the water characterized by $S = 35{\cdot}05$ ‰ and $t = 4{\cdot}6°$ is stated to be about 90 m. at Station H′ but about 300 m. at Station H″. The smoothed values of the salinity and temperature are found by reading the values represented by the projections of the points showing the salinity and temperature actually observed. The smoothed values are recorded in Tab. 14 under S′ and t' for Station H′ and under S″ and t'' for Station H″.

The values of $\frac{S'' + S'}{2}$, $\frac{t'' + t'}{2}$, $S'' - S'$ and $t'' - t'$ entered in Tab. 14 are used in the computation of the terms $k_{S''-S'}$ $(S'' - S')$ and $(k_{t''-t'} + \Delta k_{t''-t'})$ $(t'' - t')$ by means of Tab. 11. These terms will be found in the two last columns of Tab. 14.

The values of the terms $-k_{S''-S'}\ (S''-S')$ and $+\ (k_{t''-t'}+\Delta k_{t''-t'})\ (t''-t')$ applying to the depths of observation at the stations are plotted in Fig. 26, the curves showing the variation of the terms with the depth being drawn with a slight smoothing. As the value of $-k_{S''-S'}\ (S''-S')$ has been plotted instead of the value of the term $+\ k_{S''-S'}\ (S''-S')$ the value of $10^5\ (\alpha''-\alpha') = k_{S''-S'}(S''-S') + (k_{t''-t'}+\Delta k_{t''-t'})\ (t''-t')$ can be read from the figure for any depth as represented by a horizontal section of a line situated between the curves and referring to the depth in question.

The above example shows that the differences $10^5(\alpha''-\alpha')$ for the Stations H′ and H″ can be found for a series of equidistant depths by the procedure described. Isobaric surfaces at the depths 0, h, $2h$ .... Rh metres at Station H′ are considered and called the 0, 1st, 2nd ... and Rth isobaric surface. The interval h is presumed to be so small that the integer number R can be chosen such that Rh — at any rate with sufficient approximation — is equal to the depth d'_r of the reference-surface at Station H′. The differences $10^5\ (\alpha''-\alpha')$ for the depths $\frac{1}{2}h$, $\left(1+\frac{1}{2}\right)h$, $\left(2+\frac{1}{2}\right)h$ .... $\left(\mathrm{R}-\frac{1}{2}\right)h$ metres are presumed to be determined by the procedure explained above.

Table 14.

H′: φ' — 61°27′N., λ' — 3°42′W.; depth 1250m.; 1906, VI·15; $\frac{\varphi'+\varphi''}{2}$ — 61°22·5′; l — 22·5

H″: φ'' — 61°18′N., λ'' — 2°59′W.; depth 1180m.; 1906, VI·15; $0\cdot257\frac{cg}{sl}$ — 0·472; $0\cdot925\cdot10^{-10}\,cg$ — 0·000709

Isobaric surface No.	Depth Metres	S′	t′	S″	t″	$\frac{S''+S'}{2}$	$\frac{t''+t'}{2}$	S″—S′	t″—t′	$k_{S''-S'}\times(S''-S')$	$(k_{t''-t'}+\Delta k_{t''-t'})\times(t''-t')$
0	0	35·18	8·58	35·26	8·75	35·22	8·66	0·08	0·17	—5·9	2·6
1	10	·18	8·42	·26	8·75	·22	8·58	0·08	0·33	—5·9	4·9
2	20	·14	7·44	·26	8·37	·20	7·90	0·12	0·93	—8·9	13·2
3	30	·11	6·43	·25	7·82	·18	7·12	0·14	1·39	—10·4	18·3
4	40	·11	6·43	·23	7·37	·17	6·90	0·12	0·94	—8·9	12·3
5	60	·08	5·44	·21	7·18	·14	6·31	0·13	1·74	—9·7	21·6
6	80	·06	4·71	·19	6·88	·12	5·80	0·13	2·17	—9·7	26·0
7	100	·05	4·48	·19	6·80	·12	5·64	0·14	2·32	—10·5	27·4
8	150	34·99	3·52	·17	6·61	·08	5·06	0·18	3·09	—13·5	34·9
9	200	·94	2·27	·15	6·21	·04	4·24	0·21	3·94	—15·8	41·4
10	250	·93	1·75	·12	5·78	·02	3·76	0·19	4·03	—14·2	40·7
11	300	·92	1·43	·05	4·58	34·98	3·00	0·13	3·15	—9·8	29·6
12	350	·92	0·81	34·99	3·50	·96	2·16	0·07	2·69	—5·3	23·4
13	400	·92	0·34	·95	2·48	·94	1·41	0·03	2·14	—2·3	17·1
14	450	·92	0·10	·92	1·01	·92	0·56	0·00	0·91	0·0	6·6
15	500	·92	—0·07	·92	0·30	·92	0·12	0·00	0·37	0·0	2·6
16	550	·92	—0·20	·92	—0·10	·92	—0·15	0·00	0·10	0·0	0·7
17	600	·92	—0·36	·92	—0·26	·92	—0·31	0·00	0·10	0·0	0·7
18	700	·92	—0·50	·92	—0·41	·92	—0·46	0·00	0·09	0·0	0·6
19	800	·92	—0·60	·92	—0·56	·92	—0·58	0·00	0·04	0·0	0·3
20	900	·92	—0·67	·92	—0·66	·92	—0·66	0·00	0·01	0·0	0·1
21	1000	·92	—0·76	·92	—0·76	·92	—0·76	0·00	0·00	0·0	0·0
22	1100	·92	—0·85	·92	—0·84	·92	—0·84	0·00	0·01	0·0	0·1
23	1180	·92	—0·89	·92	—0·91	·92	—0·90	0·00	—0·02	0·0	—0·2

For a depth of $\left(x+\frac{1}{2}\right)h$ metre the difference $10^5\ (\alpha''-\alpha')$ is designated by $\Delta_{x,x+1}$. Just as in the expressions (16), (17) and (19) the mean value of the current at the reference-surface between Stations H′ and H″ is called v_r.

By analogy with (16) the mean value v_N of the current at the depth Nh metres may be expressed by:

$$v_N = 0\cdot257\frac{cg}{sl} - 0\cdot004\,h\sum_{x=N}^{x=R-1}\Delta_{x,x+1} + v_r \qquad (20)$$

and by analogy with (17) and (18) the mean value $v_{N,N+1}$ of the current and the intensity $q_{N,N+1}$ of

the flow through the interval between the depths Nh and (N + 1)h metres may be given respectively by:

$$v_{N,N+1} = 0{\cdot}257\,\frac{cg}{sl}\,0{\cdot}002\,h\,\cdot \left[\sum_{x=N}^{x=R-1}\Delta_{x,x+1} + \sum_{x=N+1}^{x=R-1}\Delta_{x,x+1}\right] + v_r \qquad (21)$$

and

$$\left.\begin{aligned} q_{N,N+1} = {} & 0{\cdot}925\cdot 10^{-10}\,cg\;0{\cdot}002\,h^2\cdot \left[\sum_{x=N}^{x=R-1}\Delta_{x,x+1} + \sum_{x=N+1}^{x=R-1}\Delta_{x,x+1}\right] \\ & + 3{\cdot}6\cdot 10^{-10}\cdot hslv_r \end{aligned}\right\} \qquad (22)$$

As in (19) the intensity of the flow through the area between Stations H′ and H″ below the reference-surface is called m. By analogy with (19) the intensity Q of the flow through the whole interval between Stations H′ and H″ may then be expressed by:

$$\left.\begin{aligned} Q = {} & 0{\cdot}925\cdot 10^{-10}\,cg\cdot 0{\cdot}002\,h^2\cdot \sum_{N=0}^{N=R-1}\left[\sum_{x=N}^{x=R-1}\Delta_{x,x+1} + \sum_{x=N+1}^{x=R-1}\Delta_{x,x+1}\right] \\ & + 3{\cdot}6\cdot 10^{-10}\,sld_r v_r + m \end{aligned}\right\} \qquad (23)$$

Calculations by means of expressions (21), (22) and (23), based on the same material as was used for the example in the preceding chapter are carried out in Tab. 15. As previously, the isobaric surface at the depth 1180 m. is regarded as a zero-surface and the intensity of the flow below that surface is disregarded.

The first and second columns in Tab. 15 contain the numbers and the depths of the isobaric surfaces. Opposite the intervals in the second column the third column contains the values of $\Delta_{x,x+1}$, as read from Fig. 26. In the fourth and fifth columns are found the computed values

$$\sum_{x=N}^{x=58}\Delta_{x,x+1} \text{ and } \sum_{x=N}^{x=58}\Delta_{x,x+1} + \sum_{x=N+1}^{x=58}\Delta_{x,x+1}$$

the number R for the zero-surface being equal to 59. The constants $0{\cdot}257\cdot\frac{cg}{sl}\cdot 0{\cdot}002\,h$ and $0{\cdot}925\cdot 10^{-10}cg\;0{\cdot}002h^2$ in expressions (21) and (22) are equalized $0{\cdot}472\cdot 0{\cdot}04 = 0{\cdot}0189$ and $0{\cdot}000709\cdot 0{\cdot}8 = 0{\cdot}000567$, and used for the calculation of the values for $v_{N,N+1}$, and $q_{N,N+1}$ in the sixth and seventh columns in the table. At the bottom of the seventh column the value Q of the intensity of the flow through the whole interval between the stations is recorded as the total of the figures in the column. This value of Q is about the same as was found in Tab. 13, based on the actual interval of depth.

The current-conditions between the stations considered are directly illustrated by Fig. 26. The currents at the different depths are proportional to the areas between the curves limited by lines drawn at right angles to the scale of the depth and indicating the depth of the zero-surface and the currents considered.

Correction of Calculated Values for Current and for Intensity of Flow, when the Reference-Surface is not a Zero-Surface.

Expressions (17), (18), (19) and the analogous expressions (21), (22) and (23) in the preceding chapters were used on the supposition that the reference-surface could be considered as a zero-surface and the intensity of the flow below that surface could be disregarded. If these suppositions cannot be accepted the values found for $v_{n,n+1}$, $v_{N,N+1}$, $q_{n,n+1}$, $q_{N,N+1}$, and Q by means of the above-cited expressions must be corrected. If the depths at the two stations differ much from one another the suppositions cannot usually be considered as applying, even if the reference-surface is chosen at or near the bottom, at the station with the lesser depth. The calculation of the corrections in question was based on the following considerations.

In Fig. 27, D'_r D''_r D''_y D'_z represents the lower part of the section shown in Fig. 24. The verticals D'_r D'_z and D''_r D''_y for Stations H′ and H″ are the lower parts of the verticals D'_0 D'_r and D''_0 D''_r in Fig. 24. The reference-surface D'_r D''_r is shown in both figures. The section intersects the sea bottom in the line D'_z D''_y shown in Fig. 27. For the points D'_r, D''_r, D'_z and D''_y, the depths — that is, the distances from the surface of the sea — are designated by d'_r, d''_r, d'_z and d''_y metres, and the specific volumes by α'_r, α''_r, α'_z and α''_y. It is assumed that the depth d'_r of the chosen reference-surface is less than the depth d''_y of the sea at Station H″.

Isobaric surfaces, cutting the vertical at Station H′ in points at equal distances ε metres from one another, are represented by lines marked with the numbers 0, 1, 2 . . . . . The reference-surface D'_r D''_r is the 0 isobaric surface. The distance ε is assumed to be so small that the depth d'_z at Station H′ can be equalized to zh where z is the number of the isobaric surface at the greatest depth considered.

The specific volumes at Station H′ and at Station H″ or at the sea bottom at an isobaric surface situated midway between the x^{th} and the $(x+1)^{\text{st}}$ isobaric surface are called $\alpha'_{x,x+1}$ and $\alpha''_{x,x+1}$. A difference $10^5\,(\alpha''_{x,x+1} - \alpha'_{x,x+1})$ is designated by $\Delta_{x,x+1}$.

Expressions (24), (25), (26) and (27) below are derived subject to the assumption that the sea bottom is a zero-surface instead of the surface

represented by the line $D'_r D''_r$. Thus the gradient of sea water pressure at level surfaces cutting the bottom represented by the line $D'_z D''_y$ converges to nought at the bottom. At the derivation of these expressions, considerations similar to those leading to the expressions (20), (21), (22) and (23) were used in connection with the symbols given in Fig. 27.

Referring to the whole section through stations H′ and H″ shown in Figs. 24 and 27 we have:

(1) The correction K_φ to be added to the value $\varphi_{N,N+1}$ of the current between the isobaric surfaces at the depths Nh and $(N+1)h$ metres found by means of (21), disregarding the second term φ_r on the right-hand side of this expression, may be given as:

$$K_\varphi = \varphi_r = 0{\cdot}257 \frac{cg}{sl} \cdot 0{\cdot}004\, \varepsilon \sum_{x=0}^{x=z-1} \Delta_{x,x+1} \qquad (24)$$

(2) The intensity m of the flow through the area $D'_r D''_r D''_y D'_z$ — measured in km.^{3}/hour — may be given as:

$$\left.\begin{aligned} m = {} & 0{\cdot}925 \cdot 10^{-10}\, cg \cdot 0{\cdot}002\, \varepsilon^2 \cdot \\ & \sum_{i=0}^{i=z-1} \left[\sum_{x=i}^{x=z-1} \Delta_{x,x+1} + \sum_{x=i+1}^{x=z-1} \Sigma_{x,x+1} \right] \end{aligned}\right\} \qquad (25)$$

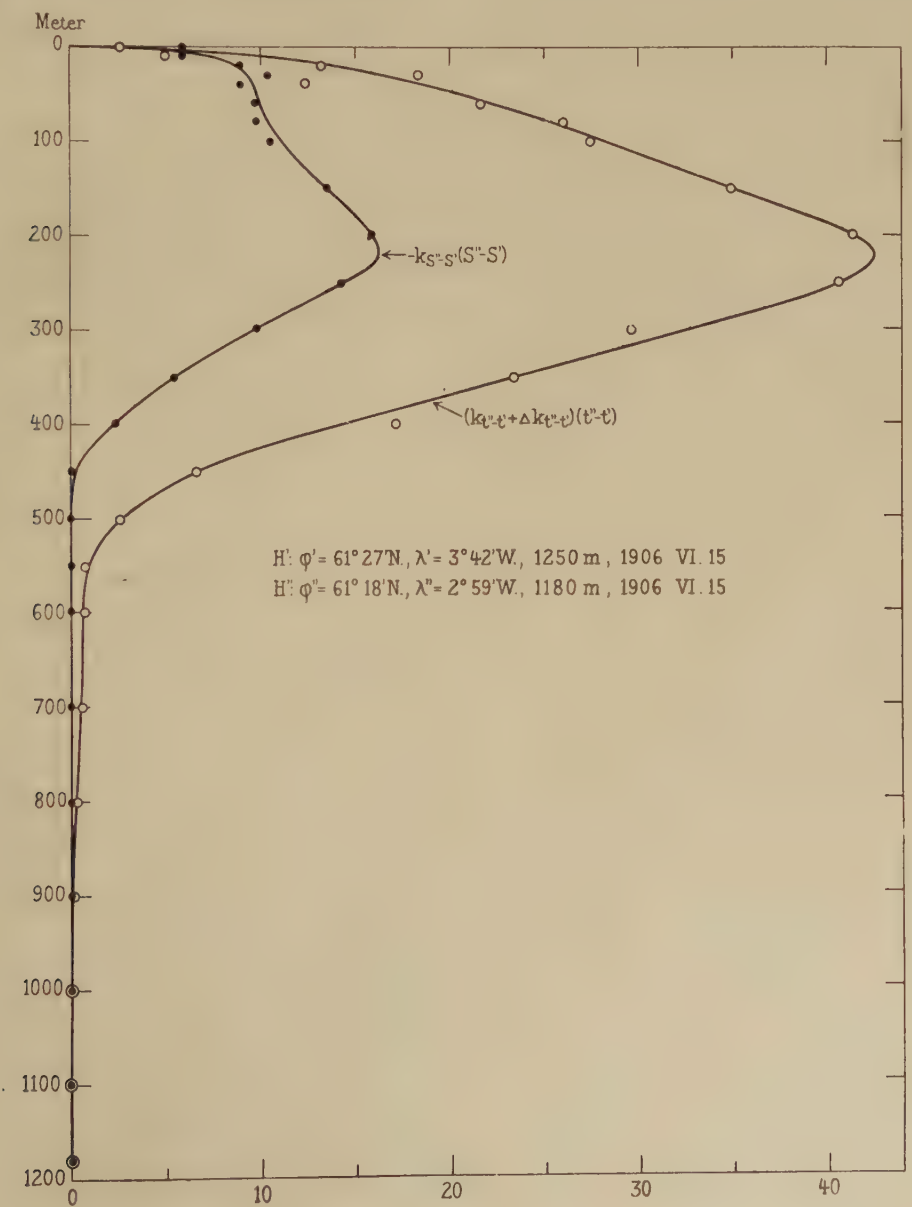


Fig. 26.

(3) The correction K_q to be added to the value $q_{N,N+1}$ of the intensity of the flow through the interval between the isobaric surfaces at the depths Nh and $(N+1)h$ metres found by means of (22) disregarding the second term $3{\cdot}6 \cdot 10^{-10}\ hsl\varphi_r$ on the right-hand side of this expression may be given as:

$$K_q = 0{\cdot}925 \cdot 10^{-10}\, cgh \cdot 0{\cdot}004\ \varepsilon \sum_{x=0}^{x=z-1} \Delta_{x,x+1} \qquad (26)$$

(4) The correction K_Q to be added to the value Q of the intensity of the flow through the whole interval between stations H′ and H″ found by means of (23), disregarding the second and third term $3{\cdot}6 \cdot 10^{-10}\ sld_r\varphi_r$ and m in this expression, may be given as:

$$K_Q = 0{\cdot}925 \cdot 10^{-10}\, cg \cdot 0{\cdot}004\ \varepsilon \left[d'_r \sum_{x=0}^{x=z-1} \Delta_{x,x+1} + \frac{1}{2}\,\varepsilon \sum_{i=0}^{i=z-1} \left(\sum_{x=i}^{x=z-1} \Delta_{x,x+1} + \sum_{x=i+1}^{x=z-1} \Delta_{x,x+1} \right) \right] \qquad (27)$$

Expressions (24), (25), (26) and (27) may also be used in connection with expressions (17), (18) and (19), these expressions being analogous to (21), (22) and (23).

It is seen from (24), (26) and (27) that the corrections K_φ, K_q and K_Q may be found when the differences $\Delta_{x,x+1} = 10^5\ (\alpha''_{x,x+1} - \alpha'_{x,x+1})$ are known for the area $D'_r\ D''_r\ D''_y\ D'_z$ in Fig. 27. Usually these differences can only be estimated with a small degree of certainty on account of the lack of observations at the bottom between the stations.

The differences $10^5\ (\alpha''_x - \alpha'_x)$ must converge to nought, when x converges to z. Supposing a continuous increase of the depth of the sea from Station H″ to Station H′, it may be assumed for the sake of simplicity that Δ_x varies linearly with x from the value Δ_0 for $x = 0$ to 0 for $x = z$. Referring to the reference-surface $D'_r\ D''_r$, the difference Δ_0 is called Δ_r, and we have

$$\Delta_x = \Delta_r \cdot \frac{z - x}{z} \qquad (28)$$

Further we have

$$d'_z - d'_r = z \cdot \varepsilon$$

and thus from (24), (26) and (27) we get:

$$K_\varphi = 0{\cdot}257\ \frac{cg}{sl} \cdot 0{\cdot}002\ (d'_z - d'_r)\ \Delta_r \qquad (29)$$

$$K_q = 0{\cdot}925 \cdot 10^{-10}\, cg \cdot 0{\cdot}002\,(d'_z - d'_r)\, h \cdot \Delta_r \qquad (30)$$

and

$$K_Q = 0{\cdot}925 \cdot 10^{-10}\, cg \cdot 0{\cdot}002\ (d'_z - d'_r) \left[d'_r + \frac{1}{3}(d'_z - d'_r)\left(1 + \frac{\varepsilon^2}{2(d'_z - d'_r)^2}\right)\right] \cdot \Delta_r$$

When the interval ε is chosen sufficiently small the last expression may be abbreviated to:

$$K_Q = 0{\cdot}925 \cdot 10^{-10}\, cg \cdot 0{\cdot}002\ (d'_z - d'_r) \left[d'_r + \frac{1}{3}(d'_z - d'_r) \right] \Delta_r \qquad (31)$$

The term $0{\cdot}925 \cdot 10^{-10} cg\ 0{\cdot}002\ (d'_z - d'_r)\ d'_r\ \Delta_r$ in (31) is involved by the correction K_φ for the current at a depth less than d'_r. The remainder of the expression (31) is the intensity m of the flow through the area of the section below the depth d'_r, m being expressed by

$$m = 0{\cdot}925 \cdot 10^{-10}\, cg \cdot 0{\cdot}00067\,(d'_z - d'_r)^2\ \Delta_r \qquad (32)$$

The special supposition expressed in (28) and previously used by J. P. Jacobsen and Aage J. C. Jensen[1]) may in some cases be approximately true, but in several cases wrong results may undoubtedly be obtained from its use. If a special supposition different from that expressed in (28) may be presumed to be valid on the basis of known facts, it may be introduced in expressions (24), (26) and (27), and then expressions other than those in (29), (30), and (31) may be derived for the corrections K_φ, K_q and K_Q.

In the cases considered in the area of the Faroe—Shetland Channel the differences Δ_x were supposed to be nil for depths greater than 800 m. Thus the corrections K_φ, K_q and K_Q were nil if the reference-surface was situated at a depth greater

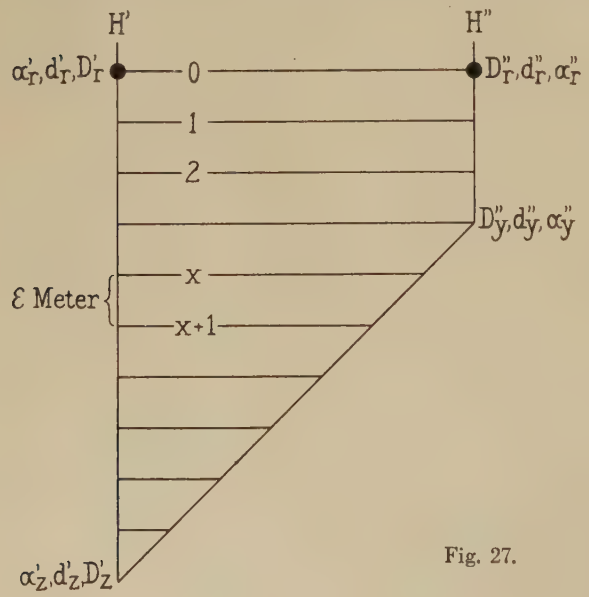


Fig. 27.

[1]) J. P. Jacobsen and Aage J. C. Jensen. Examination of Hydrographical Measurements from the Research Vessels "Explorer" and "Dana" during the summer of 1924. Rapp. et Proc.-Verb., Vol. XXXIX p. 31. Copenhague, 1926.

than 800 m. If the reference-surface was situated at a depth less than 800 m. and if the depth at the deepest station was less than 800 m. expressions (29), (30) and (31) were directly used for the determination of the corrections K_v, K_q and K_Q. If the reference-surface was situated at a depth less than 800 m. and if the depth at the deepest station was greater than 800 m., expressions (29), (30) and (31) were used with the modification that the value of d'_z was equalized to 800. The procedure in the last case is illustrated by the following example.

Fig. 28 has been based on observations taken at the two Stations H′: Sc 14A, 61°18′N., 2°59′W., 1909, IV. 26 and H″ : Sc 13A, 61°16′N., 2°08′W., 1909, IV. 26. These stations are situated in Section II (see Fig. 1) in the south-eastern side of the Faroe—Shetland Channel where the depths of the sea are 545 and 1202 m. respectively. Observations of salinity and temperature were taken at Station H″ down to 530 m. and at Station H′ down to 1200 m. The material was treated analogously to the material used in the construction of Fig. 26. The points plotted in Fig. 28 indicate the values of the terms $-k_{S''-S'}\ (S''-S')$ and $(k_{t''-t'}+\Delta k_{t''-t'})\ (t''-t')$ calculated by means af Tab. 11. Curves indicating the values of the terms at any depth from 0 to 530 m. were drawn through the plotted points. Choosing the reference-surface at the depth 530 m. and disregarding the solenoidal field

Table 16.

H′ : $\varphi' = 61°18'$N.; $\lambda' = 2°59'$W.; 1909, IV·26.
H″ : $\varphi'' = 61°16'$N.; $\lambda'' = 2°08'$W.; 1909, IV·26.
$l = 24{\cdot}6$; $0{\cdot}257\ cg/s = 10{\cdot}62$; $0{\cdot}925 \cdot 10^{-10}\ cg = 0{\cdot}000710$.

Isobaric surface No.	Depth Metres	$\Delta_{x,x+1}$	$\sum_{x=i}^{x=z-1} \Delta_{x,x+1}$	$\sum_{x=i}^{x=z-1} \Delta_{x,x+1} + \sum_{x=i+1}^{x=z-1} \Delta_{x,x+1}$
0	530		305	
		43		567
1	550		262	
		41		483
2	570		221	
		39		403
3	590		182	
		36		328
4	610		146	
		32		260
5	630		114	
		30		198
6	650		84	
		25		143
7	670		59	
		20		98
8	690		39	
		15		63
9	710		24	
		11		37
10	730		13	
		7		19
11	750		6	
		4		8
12	770		2	
		2		2
13	790		0	
		0		0
$z = 14$	810			

$$\sum_{i=0}^{i=z-1} \left[\sum_{x=i}^{x=z-1} \Delta_{x,x+1} + \sum_{x=i+1}^{x=z-1} \Delta_{x,x+1} \right] = 2609$$

below this surface, values for the current and for the intensity of the flow at any interval of depth between 0 and 530 m. could then, if desired, be determined by the same procedure as was used in connection with Fig. 26. The values had, however, to be corrected on account of the solenoidal field below 530 m.

Provisionally we assume that the salinity and temperature were known at a suitable number of depths between 530 m. and the bottom at both stations and along the bottom line of the section between the stations. The corrections in question could then be calculated by means of expressions (24), (26) and (27) in the following way.

The symbols S′, t', S″ and t'' are used for the salinity and temperature at the same depth exceeding 530 m., S′ and t' referring to a point on the vertical of Station H′ and S″ and t'' to a point either on the vertical of Station H″ or to a point on the bottom line between the stations. The values of the terms $-k_{S''-S'}$ (S″ — S′) and $(k_{t''-t'} + \Delta k_{t''-t'})$ $(t'' - t')$ could be calculated for the different depths by means of Tab. 11 and when plotted in Fig. 28, curves could be drawn representing the values of the terms at any depth between 530 m. and the bottom at Station H′.

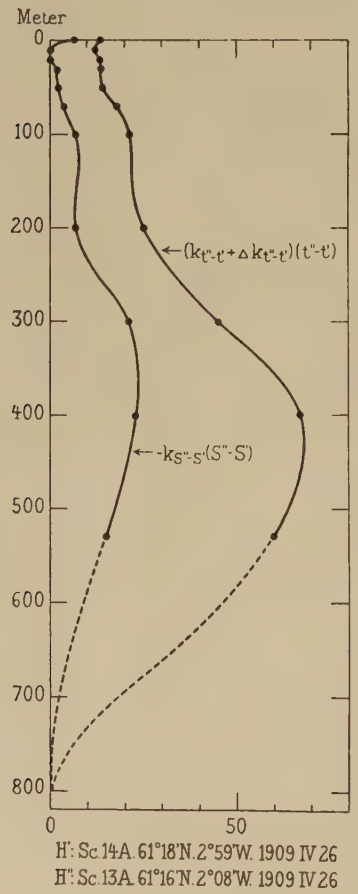


Fig. 28.

Owing to lack of observations below 530 m. at Station H″ and along the bottom line between the stations it was not possible to construct the curves in question without special suppositions. The dotted curves in Fig. 28 are drawn by estimate on the supposition that no solenoidal field exists below 800 m. and are used in the discussion to follow.

The values of $\Delta_{x,x+1} = 10^5 (\alpha''_{x,x+1} - \alpha'_{x,x+1})$ in expressions (24), (26) and (27) for the depths 540, 560 ... 800 m. were read from Fig. 28 as represented by horizontal sections of lines between the dotted curves. The reading will be found in Tab. 16, Column 3 opposite the intervals between the depths stated in Column 2. The calculation of the expressions

$$\sum_{x=i}^{x=z-1} \Delta_{x,x+1} \text{ and } \sum_{x=i}^{x=z-1} \Delta_{x,x+1} + \sum_{x=i+1}^{x=z-1} \Delta_{x,x+1}$$

is shown in the table. From the values in the table, and by means of (24) (26) and (27) we find the corrections K_v, K_q and K_Q to be:

$$K_v = \frac{10{\cdot}62}{24{\cdot}6} \cdot 0{\cdot}004 \cdot 20 \cdot 305 = 10{\cdot}5 \frac{\text{cm.}}{\text{sec.}}$$

$$K_q = 0{\cdot}000710 \cdot 20 \cdot 0{\cdot}004 \cdot 20 \cdot 305 = 0{\cdot}35 \frac{\text{km.}^3}{\text{hour}}$$

$$K_Q = 0{\cdot}000710 \cdot 0{\cdot}004 \cdot 20 \cdot \left(530 \cdot 305 + \frac{1}{2} \cdot 20 \cdot 2609\right) = 10{\cdot}7 \frac{\text{km.}^3}{\text{hour}}$$

If the differences Δ_x are supposed to vary linearly from the value at 530 m. to nil at 800 m. expressions (29), (30) and (31) may be used for the calculation of the corrections K_v, K_q and K_Q. In this case we get:

$$K_v = \frac{10{\cdot}62}{24{\cdot}6} \cdot 0{\cdot}002\,(800 - 530) \cdot 45 = 10{\cdot}5 \frac{\text{cm.}}{\text{sec.}}$$

$$K_q = 0{\cdot}000710 \cdot 0{\cdot}002\,(800 - 530) \cdot 20 \cdot 45 = 0{\cdot}35 \frac{\text{km.}^3}{\text{hour}}$$

$$K_Q = 0{\cdot}000710 \cdot 0{\cdot}002\,(800 - 530)\left[530 + \frac{1}{3}\,(800 - 530)\right] \cdot 45 = 10{\cdot}7 \frac{\text{km.}^3}{\text{hour}}$$

These values for K_v, K_q and K_Q are in accordance with the values found by means of the dotted curves in Fig. 28. In fact, these curves were drawn to establish conformity.

It should be noted that the currents at arbitrary depths between Stations H′ and H″ referred to in Fig. 28 are proportional to the areas between the curves and the horizontal lines valid for the depths considered, if these depths are less than 545 m., i.e., the depth at Station H″. For greater depths

this proportionality does not exist. The values for the intensity of the flow through a sufficiently small depth-interval of constant size are proportional to the areas between the curves and the horizontal lines in the middle of the intervals considered. This holds good for all the depths.

The Intensity of the Total Flow through a Section, calculated by means of the Salinity and the Temperature at the Bottom, when this may be considered a Zero-Surface.

Fig. 29 represents a section with the verticals H′, H″, H‴, H^{IV} ..... $H^{(p)}$, $H^{(p+1)}$ .... of the stations. The distance between two successive stations is presumed to be small. Isobaric surfaces at the depths 0, h, $2h$ ... xh, $(x+1)h$ ... metres are considered. The depth interval h is presumed to be small. The specific volumes at the sea bottom in the middle of two successive isobaric surfaces at the depths xh and $(x+1)h$ metres are called $\alpha'_{x,x+1}$ and $\alpha''_{x,x+1}$ for the left and right-hand side of the section respectively. The differences $10^5\ (\alpha''_{x,x+1} - \alpha'_{x,x+1})$ are designated as $\Delta_{x,x+1}$.

The intensity of the flow through an interval between two verticals $H^{(p)}$ and $H^{(p+1)}$ is called $Q_{(p)}^{(p+1)}$. According to (23) the value of $Q_{(p)}^{(p+1)}$ may be expressed by means of the differences between the specific volumes at the two verticals $H^{(p)}$ and $H^{(p+1)}$ for each of the depths $\frac{1}{2}h, \frac{3}{2}h, \frac{5}{2}h \ldots$ metres. As the bottom of the sea has been regarded as a zero-surface the two last terms on the right-hand side in (23) may be disregarded. By adding the values of $Q_{(p)}^{(p+1)}$ for the whole section we get that the intensity Q of the total flow through the whole section may be expressed by:

$$Q = 0{\cdot}925 \cdot 10^{-10}\, cg \cdot 0{\cdot}002h^2 \cdot \sum_{N=0}^{N=R-1} \left[\sum_{x=N}^{x=R-1} \Delta_{x,x+1} + \sum_{x-N+1}^{x=R-1} \Delta_{x,x+1} \right] \quad (33)$$

where R is the number of intervals between the isobaric surfaces in the section.

Expression (33) may also be used if the zero-surface is situated at intermediate depths. Thus the differences $\Delta_{x,x+1}$ are to be added for the area limited by the zero-surface in question. The procedure described has previously been employed by Anton Jakheln[1]) and A. B. Kiilerich[2]).

An example of the determination of the mean intensity of the total flow through Section II (see Fig. 1) in the months April, May, and June is given in Tab. 17. From Fig. 3b salinity and temperature at the bottom in the section were plotted graphically according to the depth. Salinity and temperature at the bottom for the left-hand side of Fig. 3b were designated by S_l and t_l, and by S_r and t_r for the right-hand side of the figure. From the graph the values under the headings S_l, t_l, S_r and t_r in Tab. 17 were read for the depths stated in the second column of the table. The values of $\frac{S_r + S_l}{2}$, $\frac{t_r + t_l}{2}$, $S_r - S_l$ and $t_r - t_l$ were computed and used for the calculation of the differences $\Delta_{x,x+1} = 10^5\ (\alpha''_{x,x+1} - \alpha'_{x,x+1})$ by means of Tab. 11. In the last two columns of the table are recorded the values of

$$\sum_{x=N}^{x=R-1} \Delta_{x,x+1} \text{ and } \sum_{x=N}^{x=R-1} \Delta_{x,x+1} + \sum_{x=N+1}^{x=R-1} \Delta_{x,x+1}$$

The total 4013 of the figures in the last column of the table is the value of

$$\sum_{N=0}^{N=R-1} \left[\sum_{x-N}^{x=R-1} \Delta_{x,x+1} + \sum_{x=N+1}^{x=R-1} \Delta_{x,x+1} \right] \quad \text{in (33)}$$

For Section II, situated between 61° and 62°N. Lat. the value of $0{\cdot}925 \cdot 10^{-10}\, cg$ may be equalized to 0·000708 (see Tab. 12). As the value of h in the case considered is 50 m. we get:

$$Q = 0{\cdot}000708 \cdot 0{\cdot}002 \cdot 2500 \cdot 4013 = 14{\cdot}2 \ \frac{\text{km.}^3}{\text{hour}}$$

This value of Q is given in Tab. 6 as the intensity of the total flow through Section II in the months April, May, June.

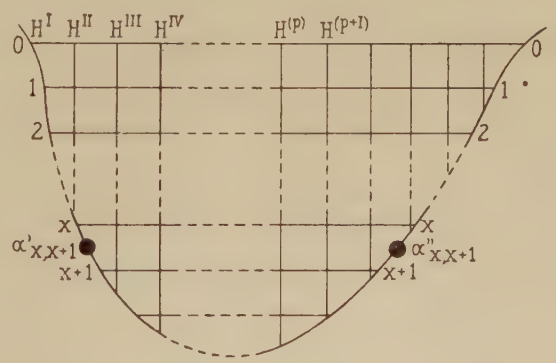


Fig. 29.

[1]) Anton Jakheln. The Water Transport of Gradient Currents. Geofys. Publ., Vol. XI, No. 11. Oslo, 1936.

[2]) A. B. Kiilerich. The Godthaab Expedition 1928. Medd. om Grønland, Bd. 78, No. 5. København, 1939.

Table 17.

N	Depth Metres	S_l	t_l	S_r	t_r	$\frac{S_r+S_l}{2}$	$\frac{t_r+t_l}{2}$	S_r-S_l	t_r-t_l	$k_{S_r-S_l} \times (S_r-S_l)$	$(k_{t_r-t_l} + \Delta k_{t_r-t_l}) \times (t_r-t_l)$	$\Delta_{x,x+1}$	$\sum_{x=N}^{x=R-1} \Delta_{x,x+1}$	$\sum_{x=N}^{x=R-1} \Delta_{x,x+1} + \sum_{x=N+1}^{x=R-1} \Delta_{x,x+1}$
0	0													
		35·21	7·2	35·31	8·2	35·26	7·7	0·10	1·0	—7·4	14·0	6·6	218·8	431·0
1	50	·22	7·2	·33	8·3	·28	7·8	0·11	1·1	—8·2	15·6	7·4	212·2	417·0
2	100	·21	7·1	·34	8·3	·28	7·7	0·13	1·2	—9·6	17·0	7·4	204·8	402·2
3	150	·21	6·9	·34	8·2	·28	7·6	0·13	1·3	—9·6	18·5	8·9	197·4	385·9
4	200	·20	6·7	·34	8·1	·27	7·4	0·14	1·4	—10·4	19·6	9·2	188·5	367·8
5	250	·18	6·5	·33	8·0	·26	7·2	0·15	1·5	—11·1	21·0	9·9	179·3	348·7
6	300	·16	6·1	·30	7·8	·23	7·0	0·14	1·7	—10·4	23·5	13·1	169·4	325·7
7	350	·11	5·6	·28	7·5	·20	6·6	0·17	1·9	—12·6	25·6	13·0	156·3	299·6
8	400	·04	4·5	·24	7·2	·14	5·8	0·20	2·7	—14·8	34·0	19·2	143·3	267·4
9	450	34·98	2·7	·19	6·6	·08	4·6	0·21	3·9	—15·6	45·2	29·6	124·1	218·6
10	500	·96	1·5	·14	5·2	·05	3·4	0·18	3·7	—13·4	38·5	25·1	94·5	163·9
11	550	·95	0·7	·08	3·6	·02	2·2	0·13	2·9	—9·7	26·7	17·0	69·4	121·8
12	600	·95	0·2	·03	2·5	34·99	1·4	0·08	2·3	—6·0	19·8	13·8	52·4	91·0
13	650	·94	—0·2	34·99	1·7	·96	0·8	0·05	1·9	—3·8	15·2	11·4	38·6	65·8
14	700	·94	—0·4	·97	1·0	·96	0·3	0·03	1·4	—2·3	10·6	8·3	27·2	46·1
15	750	·94	—0·6	·95	0·5	·94	0·0	0·01	1·1	—0·8	8·1	7·3	18·9	30·5
16	800	·94	—0·7	·94	0·1	·94	—0·3	0·00	0·8	0·0	5·8	5·8	11·6	17·4
17	850	·93	—0·7	·94	—0·2	·94	—0·4	0·01	0·5	—0·8	3·7	2·9	5·8	8·7
18	900	·93	—0·8	·93	—0·5	·93	—0·6	0·00	0·3	0·0	2·2	2·2	2·9	3·6
19	950	·93	—0·8	·93	—0·7	·93	—0·8	0·00	0·1	0·0	0·7	0·7	0·7	0·7

20	1000	·93	—0·8	·93	—0·8	·93	– 0·8	0·00	0·0	0·0	0·0	0·0	0·0	0·0
21	1050	·93	—0·8	·93	—0·8	·93	—0·8	0·00	0·0	0·0	0·0	0·0	0·0	0·0
22	1100	·93	—0·8	·93	—0·8	·93	—0·8	0·00	0·0	0·0	0·0	0·0	0·0	0·0
23	1150	·93	—0·8	·93	—0·8	·93	– 0·8	0·00	0·0	0·0	0·0	0·0	0·0	0·0
24	1200	·93	—0·8	·93	– 0·8	·93	—0·8	0·00	0·0	0·0	0·0	0·0	0·0	0·0
25	1250	·93	—0·8	·93	—0·8	·93	—0·8	0·00	0·0	0·0	0·0	0·0	0·0	0·0
26	1300	·93	—0·8	·93	—0·8	·93	—0·8	0·00	0·0	0·0	0·0	0·0	0·0	0·0
27	1350	·93	—0·8	·93	—0·8	·93	—0·8	0·00	0·0	0·0	0·0	0·0	0·0	0·0
28	1400													4013

The Great Exchange of Water Masses along the Norwegian Coast, 1940.

By

Jens Eggvin.

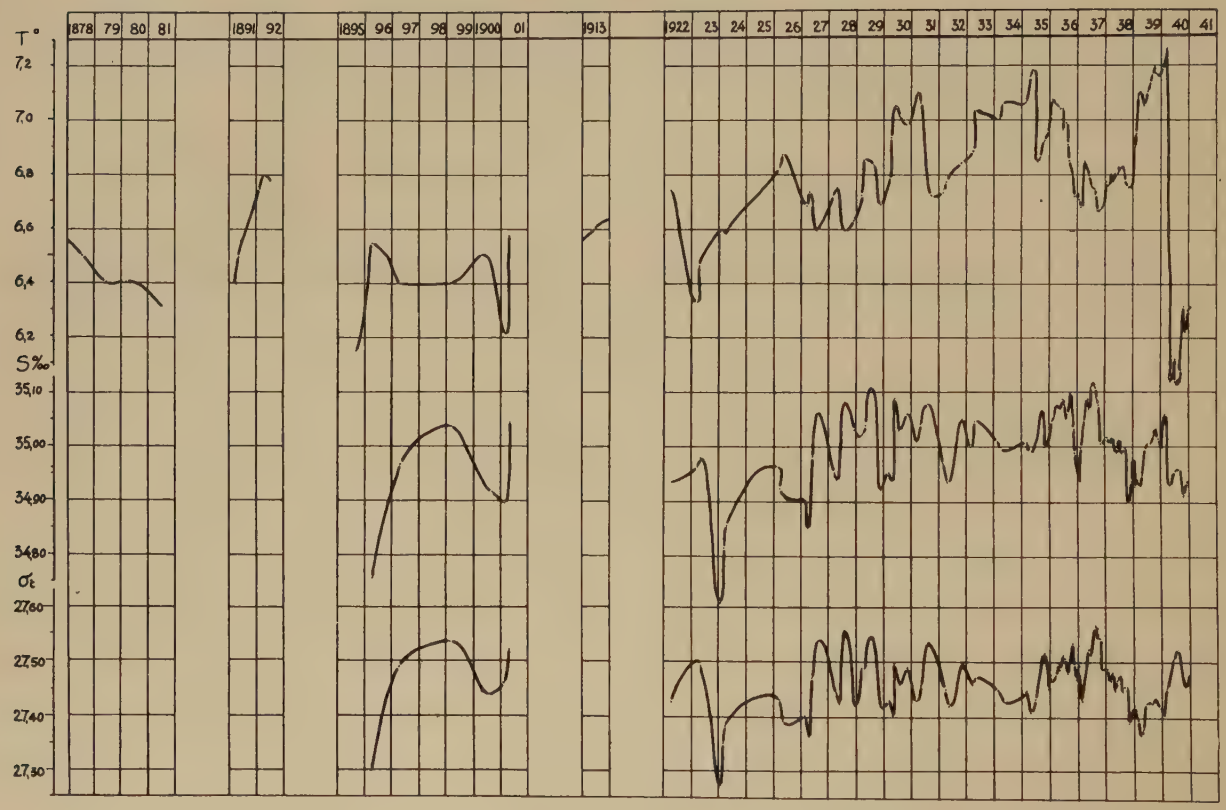


Fig. 1. Temperature, Salinity and Density at the bottom of the Vestfjord. The year of observation is given in the head-line.

IN Scandinavia and over extensive parts of the Norwegian Sea the winter of 1940 was extraordinary cold. The low temperature of the air combined with the outflow of surface water from land, along the entire coast from Lista to West Finmark, was bound to assert itself on the temperature of the sea and — subsequently — on the deep-water currents as well. It will be shown below that the cooling of the water was actually greater in the deep than at the surface along this coast. The final result was that the water-exchange during the spring, the summer and the autumn was more conspicuous in deep water along the Norwegian coast and in the fjords than ever previously observed in the oceanographic history of this country.

The Vestfjord is the area within the Norwegian waters from which the most extensive oceanographical material exists. For 20 years observations have been made in the various depths from surface to bottom several times during each year. For 5 years now, since the establishment of a permanent oceanographical station at Skrova — at the initiative of the Directorate of Fisheries — fortnightly observations on temperature and salinity have been made, extended during December and January to weekly observations whenever permitted by weather or other conditions. Material also is available as far back as 1878, collected by the Norwegian North-Atlantic Expedition 1876—78; as shown by Fig. 1, however, observations were not made in all years prior to 1922.

Fig. 1 shows the bottom-temperature at the Vestfjord from 1878 to 1941, with the above-mentioned breaks. Most of the observations were made at 300 m. depth and chiefly in the neighbourhood of Skrova. Occasionally — when in some years prior to 1922 observations have not been made within this area, observations have been chosen from nearby stations or from areas of the fjord where it is known — from experience — that the bottom-temperature conditions are similar to those of the Skrova district. From the figure it will be observed that the bottom-temperature prior to and around the beginning of this century was lower than that recorded from 1924 until March 1940. 1892, however, is an exception as the temperature of the bottom-water in that year was relatively high. It will be seen that the temperature has been rising from 1923 until March 1940, the continuity in the increase, however, being broken by occasional decreases. Thus, a decrease took place from 1935 to 1936 and further to 1937 keeping about level in 1938 but again rising from 6·76° in December 1938 almost continuously throughout 1939 till March 1940 when culminating with the highest bottom-temperature: 7·26°, ever observed within the fjord. Then the forceful water-exchange took place, caused by an inflow into the fjord of water considerably colder, slightly less saline and somewhat heavier than that present. *This brought the temperature of the bottom-water down from the maximum height to the lowest minimum ever observed in this part of the fjord.*

It is a well-known fact that during autumn and winter most lakes cool down to an even temperature from surface to bottom. This phenomenon also exists in certain oceanic areas and in some threshold fjords, but is conditional on approximately even salinity at all depths. Fridtjof Nansen has shown that such conditions exist within a certain area of the Norwegian Sea between Jan Mayn and West Spitzbergen. In the Vestfjord as well as in the major part of the Norwegian coastal waters similar conditions do not exist, since considerably higher salinities are normal in lower layers than at or near the surface. Here we have to deal with two different types of water: coastal water of comparatively low salinity as an upper layer and the heavier Atlantic water of higher salinity as a lower layer. Ordinarily the coastal water of the Vestfjord, by February—April, has a temperature of 2° to 4°C. while that of the deep water (from some 180 m. to the bottom) is about 6·7°C. Within the boundary-layer between these water types, salinity as well as temperature rise rapidly, and this boundary-layer is just that within

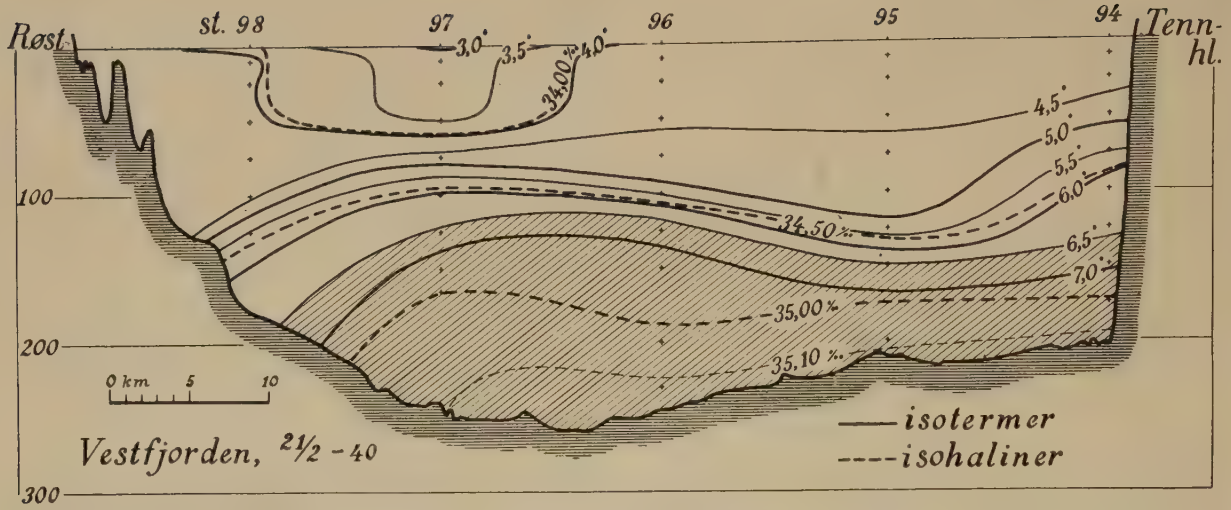


Fig. 2. Temperature and Salinity in a section taken across the entrance to the Vestfjord, on February 21st, 1940. The area where $t° > 6{\cdot}5°$ C. is hatched.

which the major part of the Norwegian skrei-fishery takes place. No cooling of the surface-water will ever make the water so heavy that it is able to sink through the more saline deep water and reach the bottom. Renewal of deep water, thus, cannot take place by cooling of surface-water in the same area, but must occur by inflow of water. As recorded by Fig. 1, an extensive renewal of deep water took place in the spring of 1940, and the question as to "wherefrom and how?" therefore is obvious. Previous observations from an area SSW. off Røst, the estuary of the Vestfjord, record fairly high salinities at the surface, at times almost as high as those of the deep water inside the fjord. The intensively cold winter of 1940 must have cooled this surface-water and made it sink fairly deep, though without reaching the bottom. From the following it will be seen that the possibility of inflow of just this water almost with certainty may be considered the real cause of the deep water renewal.

Figs. 2 and 3 record temperature and salinity sections across the entrance to the fjord on February 21st and April 5th, 1940, respectively. A considerable decrease of bottom-temperatures from February to April will be recognized. Also it will be noticed, from Fig. 3, that a patch of colder water exists at 100—140 m. depth (St. 229 and 230) at the same time recording lower salinity than deeper as well as higher layers. According to current calculations this water must be *en route* towards

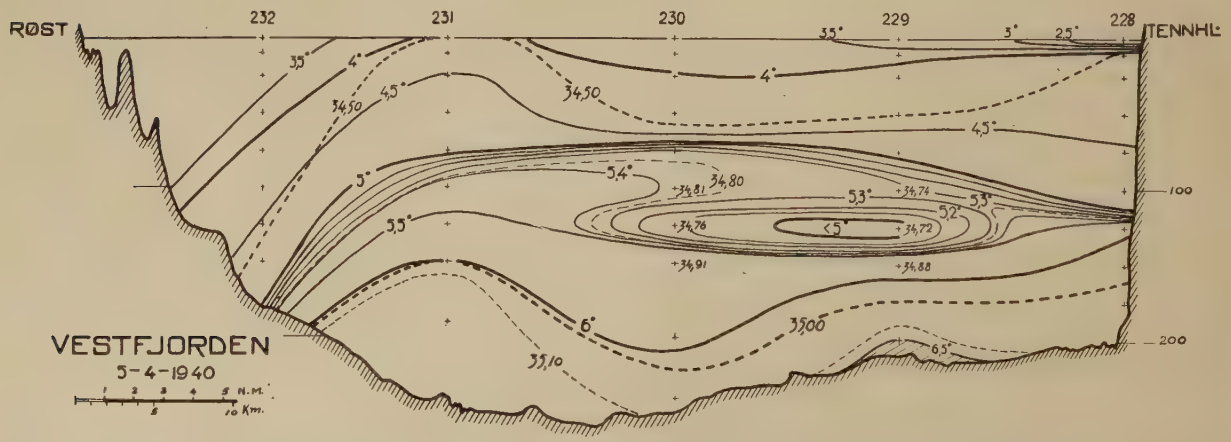


Fig. 3. Temperature and Salinity in a section taken across the entrance to the Vestfjord, on April 5th, 1940. The area where $t° > 6{\cdot}5°$ C. is hatched.

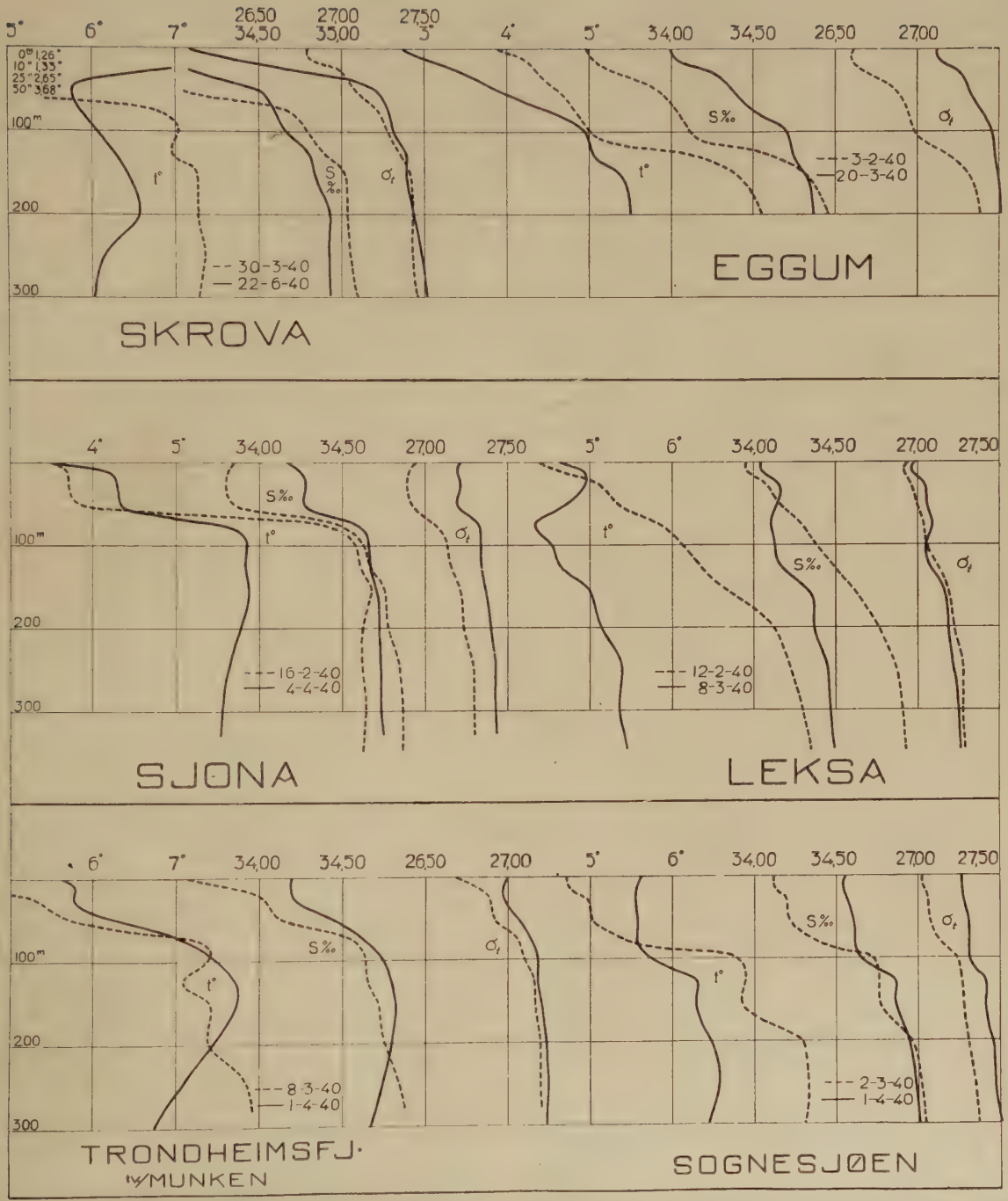


Fig. 4. Temperature ($t°$), Salinity (S ‰) and Density (σ_t). The position of the Stations of observation is given in Fig. 6.

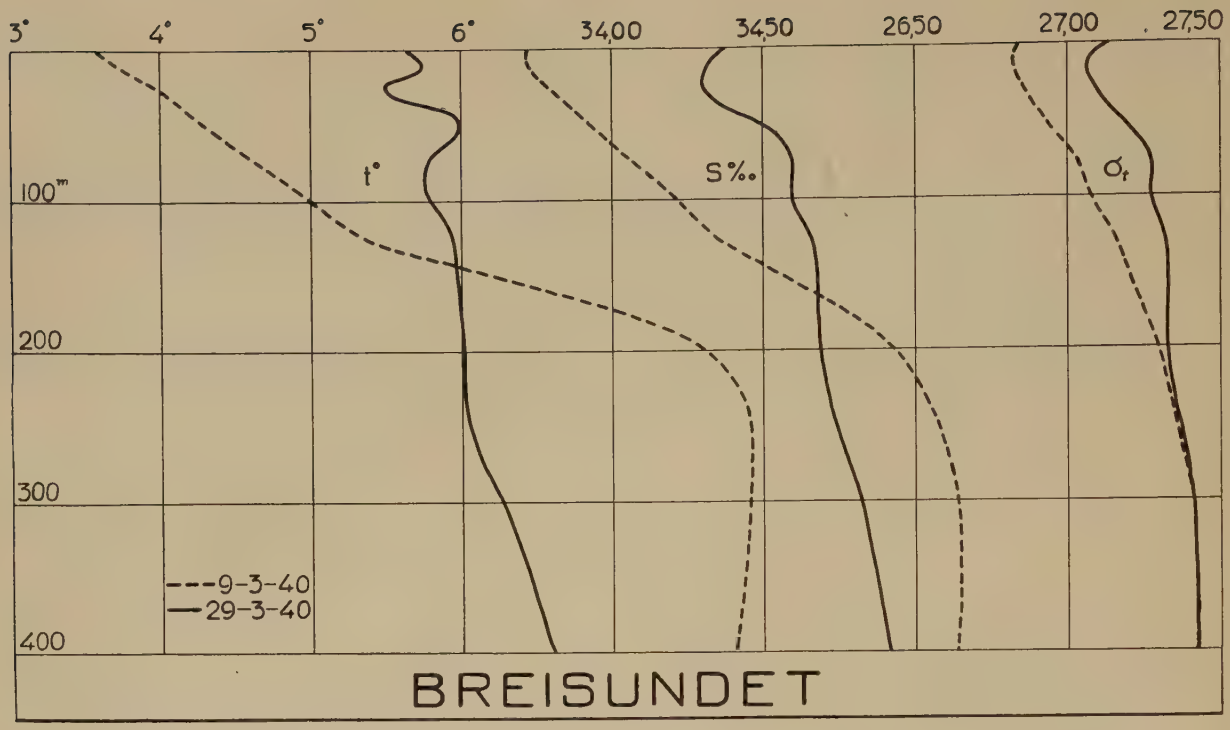


Fig. 5. Temperature, Salinity and Density at Breisund, Møre, on March 9th and 29th, 1940.

the fjord; considering this fact and the general character of the water the conclusion must be that the water must originate from surface-water farther out in the sea of a slightly higher salinity (about 34·70 $^0/_{00}$) that has been cooled and been sinking before reaching the section under discussion.

The density of this type of water is greater than that of the bottom-water present in the inner part of the fjord (near Skrova) before the exchange and most probably the said type of water is just that, which forms the bottom-water in the fjord after the exchange. The above-mentioned density almost equals that of the new bottom-water (near Skrova); during the inflow the water to some extent must mix with the warmer and more saline water present, causing as progressing a minor rise in temperature as well as salinity — without necessarily causing any greater change in density — as also confirmed by later observations during summer and autumn at Skrova.

As early as February 21st, no indication of any exchange of water was noted, on April 5th, however, the exchange was in full progress in the outer part of the fjord (Fig. 3); another section in the Vestfjord — Mosken—Landegode — made on the same day shows that a certain part of the old water type is still present mid-fjords, the rest otherwise exchanged. On March 30th observations near Skrova show that the inflow of cold water had not reached that far; resuming the observations (temporarily postponed due to the outbreak of war) on June 22nd, however, it appears that by then the exchange was complete (Fig. 4); and conditions have not altered during summer and autumn, disregarding a slight rise of temperature late in the autumn (Fig. 1).

At the banks outside Lofoten (Eggum) an exchange of the water masses took place between February 3rd and March 5th (the bottom-temperature decreased from 7·09° to 5·21°C.); here the exchange took place earlier than within the Vestfjord. This is in accordance with earlier experience: great changes in water composition always happen earlier outside Lofoten than in the Vestfjord. At Sjona, Helgeland, the great exchange took place between February 18th and April 14th; the temperature of the deep water dropped more than 1·5°. The salinity also decreased, but the temperature of the inflowing water was so low that it was heavier than the water present (Fig. 4).

It does not surprise that at Trøndelag — as at Lofoten — the exchange happens earlier in coastal waters than within the fjords. Thus off Leksa, outside the Trondheimsfjord, the exchange took place between February 12th and March 8th (Fig. 4), while a section across the fjord near Trondheim, made on February 18th, March 8th and April 1st proves that the change took place within the period between the two latter dates. In Fig. 4 the conditions are recorded for a station on this section for

Ingøy
VARANGERFJ.
70°
30°
26°
22°
18°
Eggum
RØST
Skrova
TENNHL.
68°
Sjona
66°
14°
Leksa
64°
Trondheimsfj.
Breisundet
62°
6°
10°
Sognesjøen
60°
FÆRDER
JÆREN

Fig. 6.

both dates; from this it is evident that the colder water of lower salinity that has come in has lifted the bottom-water — formerly present — and caused an outflow of the water in upper layers. At the Breisund, Møre, the exchange took place between March 9th and 29th; the bottom-temperature dropped from 7·81° to 6·61°C., the lowest temperature ever observed here. The salinity also decreased: from 35·14 ‰ to 34·92 ‰ (Fig. 5). Observations have been recorded here annually since 1927.

According to the programme prepared for the permanent oceanographical station at Sognesjøen (erected by the Fisheries Directorate) observations should be made weekly during the months of December and January, otherwise fortnightly. Early in the winter, however. it was evident that conditions would be somewhat different from normal and the keeper of the station was ordered to make observations weekly also after January. At eleven depths between surface and bottom (300 m.) series of observations, therefore, exist — after January — for February 3rd, 10th, 17th and 24th, March 2nd, 11th, 16th and 23rd, and for April 1st and 8th.

This material shows that the exchange of deep water took place over a longer period: February 17th—March 11th—April 8th; within two periods. however, the progress of the exchange has been more rapid that in others, thus March 2nd—11th and March 23rd—April 1st, continuing until April 8th. During the week March 2nd to 11th the density increased more than in the latter period.

The observations show that the transport of surface-water away from the coast commenced as early as mid-January permitting deeper layers of warmer water of greater salinity to rise towards the surface. The salinity of the surface-water was increasing until early in April (Fig. 7). Water that close to the coast normally is to be traced at 75—100 m., gradually rose right to the surface. At Sognesjøen water of 34·00 ‰ salinity reached the surface by February 20th and by the end of March water of 34·50 ‰ salinity came to the surface. From Fig. 7 it will be noticed that the salinity and density at the surface (1 m. depth) was higher from January to April, 1940, than previously observed since the erection of the station (February 1935). The heavy cold caused cooling of the salt and fairly warm water when reaching the surface, thereby it became heavier and sank through the layers immediately below. This process being steadily repeated, the salinity near the surface being high — the water thus heavier — the sinking — and thereby the cooling — reached comparatively great depths. At the Sognesjø, for instance, the cooling reached a depth of more than 100 m. by the first week of April. The water at this depth was in this way cooled to some 2°C. below normal. On the other hand, the surface temperature kept very near to the normal in spite of the cold weather. the reason being the continued up-going flow of the deeper warm water (see Fig. 7). Simultaneously

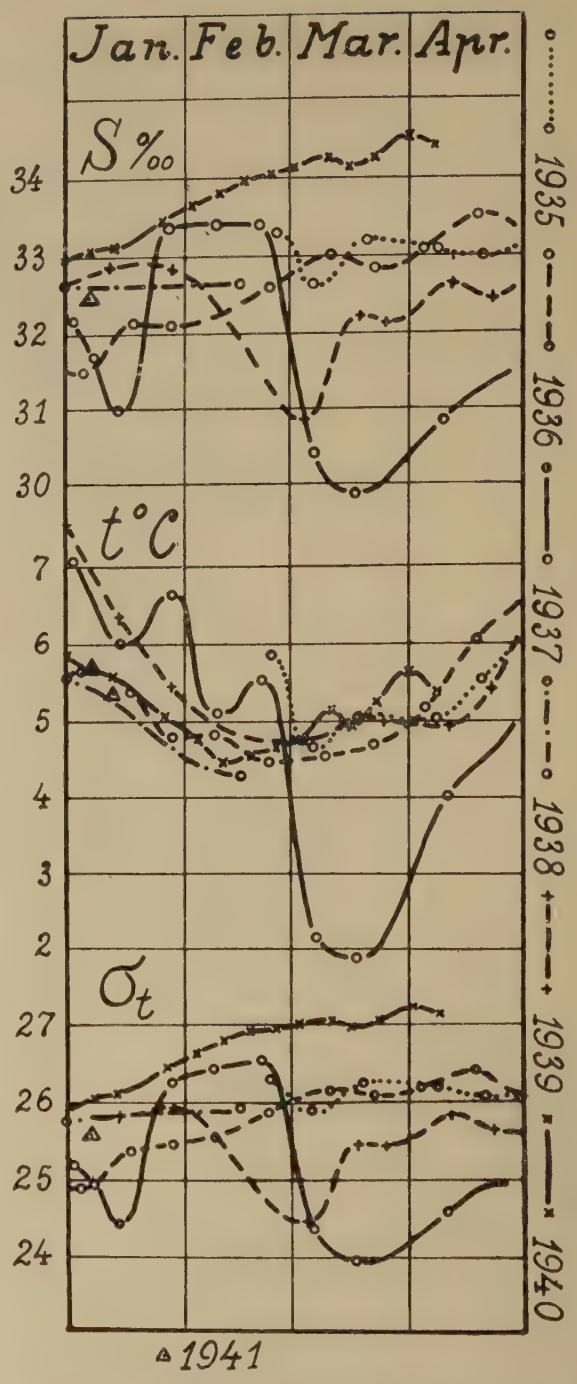


Fig. 7. Salinity, Temperature and Density in the Sognesjø at 1 m. depth, I. 1 to IV. 8, 1940, compared with the available observations for the same period in the years 1935—39. Some few observations from 1941 have been included. The 1940-curves are given in the figure by cross (indicating an observation) and line.

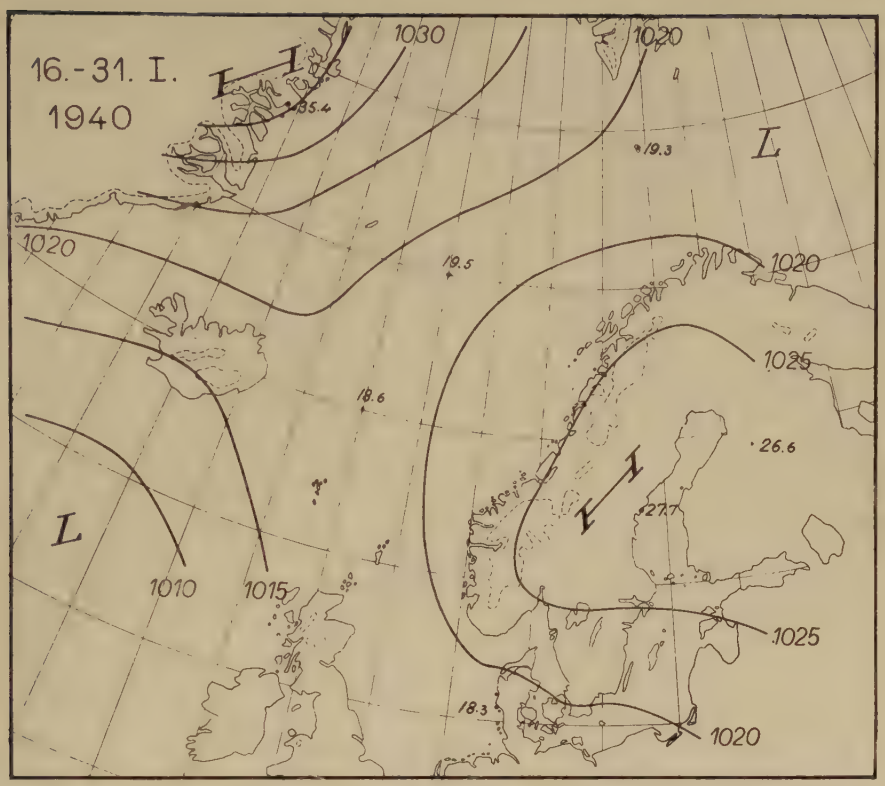


Fig. 8a. Distribution of Air-Pressure, I. 16—31, 1940.

an exchange of water took place in deeper layers: from 150 to 300 m.; the latter type of water had come in from the ocean and had been formed in a way similar to that described for the upper 100 m. layer of the inner Sognesjø, by cooling and sinking. This process taking place at greater distance from the coast with surface water of higher salinity, the cooled water became heavier and the inflow thus forced its way below the upper water layers near the coast.

As already mentioned the exchange in the estuary of the Sognefjord (Sognesjøen) extended over a longer period: February 17th to April 8th, when observations were temporarily stopped. The exchange at greater depths within the fjord must have taken place *after* this date, at the innermost fjord-arms probably not till late summer or autumn. Thus, Professor B. Helland-Hansen (Bergens Arbeiderblad, November 20th, 1940) has shown that the exchange of water in the deeper parts of the inner Nordfjord, Innvikfjord, occurred between July and September, when the temperature at 300—400 m. depth dropped to 6°C. and the salinity to about 34·60 ‰ or less than ever before recorded. The Geophysic Institute have had observations made here every year since 1925. The Innvikfjord is separated from the outer fjord by an undersea ridge: the "Andesnesryggen", a threshold some 120 m. below the surface.

Observations made at the initiative of the Fisheries Directorate during the cruise to the Vesterålen, Troms and West-Finmark (August—September) prove that also here an exchange of deeper water has taken place.

This extensive exchange of water is characterized by the fact that the inflowing water masses were considerably colder, of slightly lower salinity and greater density due to the low temperature, when compared with the conditions of the water present prior to the exchange.

The Causes of the Exchange.

The atmospheric pressure distribution during the period of the most intense cold is recorded in Fig. 8, the three charts of which show the mean pressure of the periods January 16th—31st, February 1st—15th, and 16th—21st. It will be noticed that a stationary high-pressure existed above Scandinavia and a high-pressure above Greenland; between these a trough of somewhat lower pressure — although higher than normal for the season — existed with an axis from Svalbard to Iceland. This axis moved slowly towards the Norwegian coast.

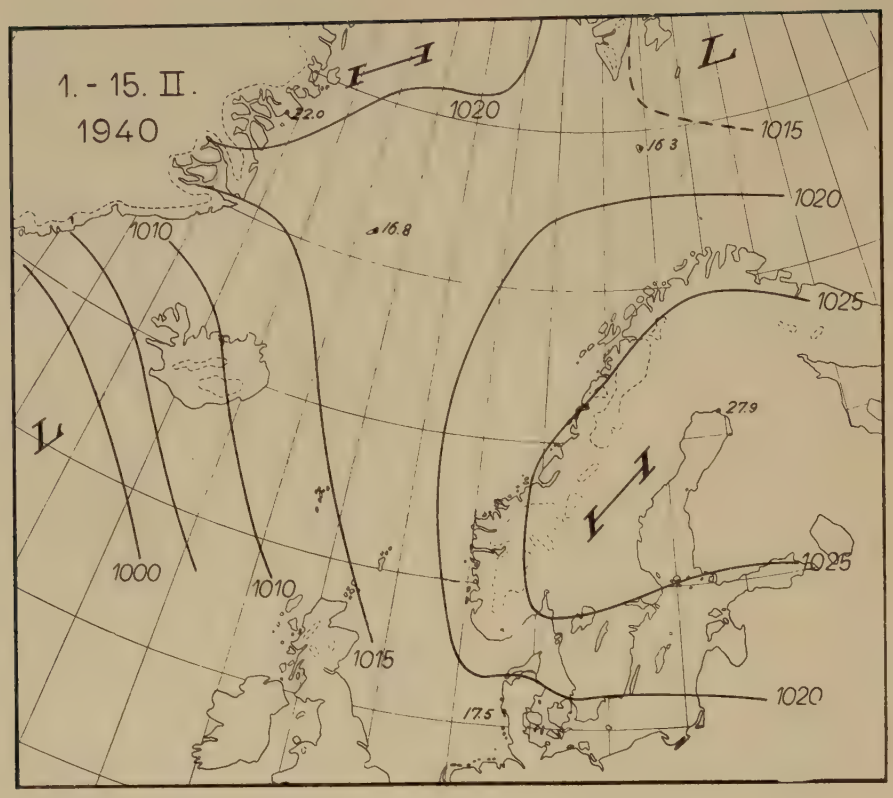


Fig. 8b. Distribution of Air-Pressure, II. 1—15, 1940.

A much lower pressure is recorded SW. of Iceland. This combination caused comparatively warm air-currents moving from the south towards NW.-Europe, to be stopped by the higher pressure and turned westward and thereby causing the temperature at Iceland and S.-Greenland to rise above normal. Part of the warmer air-current, although in minor quantities, also passed through the channel between the high-pressures, thereby causing a mild winter at Svalbard.

Due to the prolonged radiation over Scandinavia and such parts of the ocean which were mastered by the stationary high-pressure, the air-temperature in these regions dropped far below normal; a strong cooling of the fjord-waters as well as the water masses at or near the Norwegian coast was the unavoidable result. The coastal stations of southern and western Norway as well as at Trøndelag record the strongest cold between January 15th and February 20th, another cold spell happened during the week March 11th—17th. In northern Norway the cold lasted until the end of March barring a brief milder period by the end of January/beginning of February. As an example of the temperature-distribution it may be mentioned that the week February 5th—11th, at Lista, Sula in the Trøndelag and Røst recorded air-temperatures of 10°, 6° and 2°C. respectively *below* the seasonal means, while the Faroes, N.-Iceland and Bear Island recorded 3°, 6° and 9°C. *above* the respective means.

How far from the Norwegian coast — in north and west — the water masses have been subject to strong cooling it is difficult to determine; according to observations attainable, however, it seems reasonable to include the northern North Sea, the coastal region as far out as near the above-mentioned low-pressure channel, and in north as far as half-way to the Bear Island.

Pressure-charts and air-temperature observations were kindly placed at our disposal by Mr. S p i n n a n g r, in charge of the Meteorological Institute at Bergen.

Along the coast from Lista to Finmark great water masses were from time to time carried away from the coast. They had to be replaced by the inflow of deeper, salter and warmer water masses; the outflow of fresh water from land at the same time being minimal, the salinity of the surface-water would be fairly high (Fig. 9). In this way the water became heavier than normal and the strong cooling made it sink deeper than ordinarily, in consequence causing the water down to almost 100 m. to decrease in temperature below the normal.

The upper water layers being heavier their flow

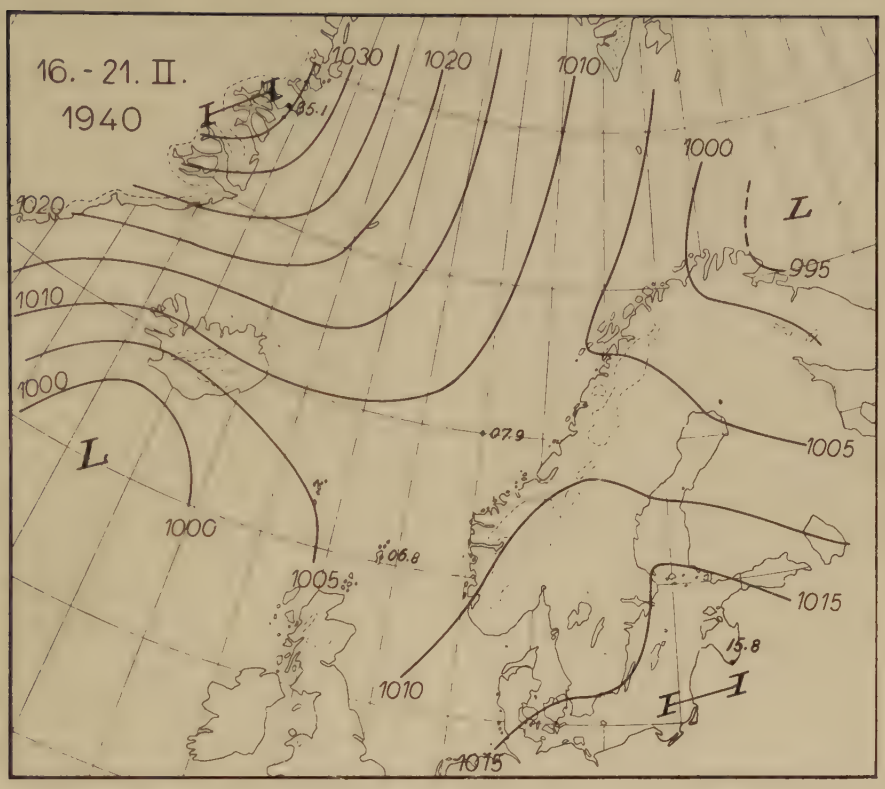


Fig. 8c. Distribution of Air-Pressure, II. 16—21, 1940.

across shallower thresholds was fairly easy thus causing the light water in fjords or basins in coastal waters surrounded by such thresholds to be replaced by the inflowing heavier water masses.

The type of water flowing into fjords or basins not enclosed by such thresholds must have been formed further out where the water is more homogeneous in upper layers down to about 200 m. or more.

Will the Low Temperature in the Deep last?

The thermographs on board the three coastal liners running in the coastal waters Oslo—Varangerfjord show that the surface temperature of the entire coast — generally speaking — during the three last months of the year 1939, was somewhat below the 5-year mean, 1935—1939, for the corresponding months. In each of the months from which observations exist, also 1940 records temperatures lower than the corresponding 5-year means. No mean temperatures exist for the months of April and May, 1940; for June and July they exist for the route Bergen—Oslo only. The months of August, September, October and November all had very low temperatures and particularly is this the case for August and September. At Sletta (near Haugesund) and the Korsfjord (south of Bergen) the August temperatures were 5·1° and 3·6°C. below mean, as far as September is concerned the corresponding figures were 3·6° and 4·6°C. All the way from Ferder to Varangerfjord the August—November temperatures are recorded below normal, and also December records lower temperatures when reviewing the entire coast.

Generally speaking the surface temperature along the entire Norwegian coast (disregarding the period when no observations were made) was below any previous record since the commencement of the thermograph-service in 1935. Compared with the above-mentioned records of lower temperatures in deeper layers the conclusion must be *that the storage of heat in the coastal water masses during summer and autumn 1940, was less than in any previous year.*

Interrupted by brief intervals the surface-temperatures of the Norwegian Sea as well as the Barents Sea (as far as observations are available) have been steadily increasing from 1923 till the autumn of 1939. Due to this rise in temperature the isotherms in deeper layers have been moving N. and NE.-wards, and correspondingly some fisheries have followed this move. The drop in temperature

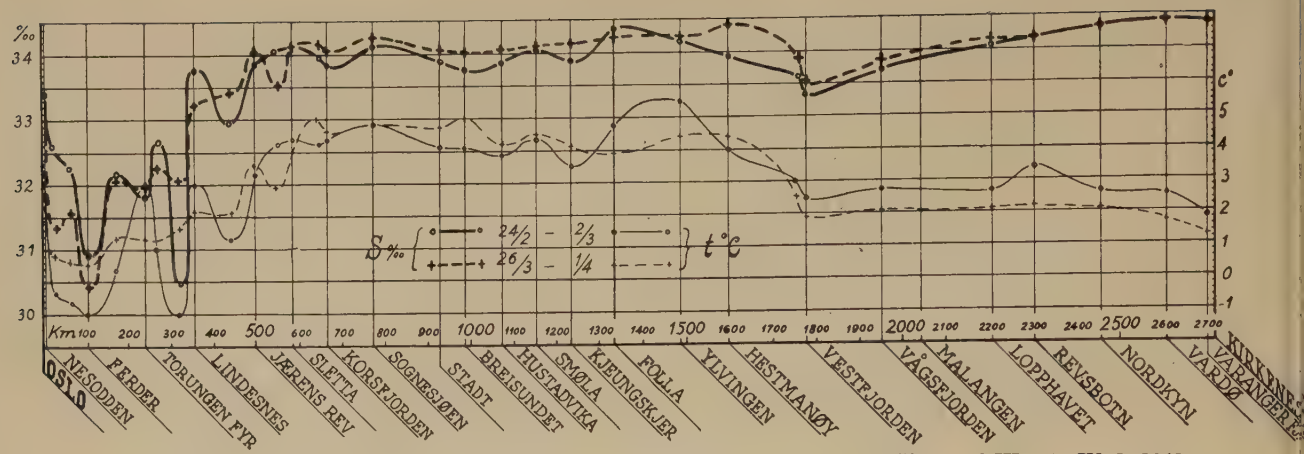


Fig. 9. Salinity and Temperature at 4 m. depth along the Norwegian coast, II. 24—III. 2 and III. 26—IV. 1, 1940.

in the Norwegian Sea and adjacent fjords was greater than the total rise during the said period, and obviously it is of the greatest biological importance whether the situation of 1940 be long lasting or of passing nature only:

During the period of exceptional cold in Scandinavia, Iceland and the region south of Iceland recorded comparatively high temperatures. Thus, from January 15th to March 24th the temperature at northern Iceland was about 1·5°C. above the means of the season, that of southern Iceland some 0·8°C. above mean. Within the same period the Faroe Islands temperature was as usual. Any special cooling of the water masses could not take place in this region as compared to that occurring off the Norwegian coast, the Skagerak and the Kattegat. No indication exists as to extraordinary cooling of the water in the NE.-corner of the Atlantic from where Atlantic water moves towards the Norwegian Sea. Thermograms from the S/S "Lyra" on the route Bergen—Iceland, on the contrary, record temperatures in the Faroe—Shetland channel slightly higher than in previous years; this also was the case between the Faroes and Iceland. This vessel made six cruises along the said route between January 23rd and April 1st, 1940 (see Fig. 10).

consequently will be lighter than normal. As mentioned above the Atlantic water south of the Faroe Islands is unchanged and thus of higher salinity when approaching the less saline bottom-water now present along the Norwegian coast; when passing north along the coastal bank — and partly south in the Norwegian Channel — normal conditions will gradually be re-established, first of all along the slope and later on in coastal waters as well as in fjord-deeps in direct connection with the open sea.

Observations on temperature and salinity at the permanent stations of the Fisheries Directorate already show that such re-establishment of normal conditions has commenced. Thus, in January 1941, normal[1]) conditions have already been re-established on the outer banks at Lofoten (Eggum) and on the west-coast (Sognesjøen), while the temperature conditions on the West-Finmark banks (Ingøy) are still below normal[1]).

Within the fjords the cold water must still (January 1941) be expected to the present. Observations at various depths in the Vestfjord also prove that this is as yet correct. The following table records the temperature distribution at various depths within the Vestfjord (Skrova) and on the banks outside Lofoten (Eggum) during January

Depth in m.		1	10	25	50	75	100	125	150	200	250	300
Skrova	11/I, 1941	4·53	5·20	5·48	5·48	5·42	5·61	5·79	5·95	6·62	6·43	6·25
	13/I, 1940	4·34	4·49	4·66	4·95	7·02	7·12	7·08	7·17	7·18	7·12	7·16
Eggum	13/I, 1941	4·78	4·92	5·73	6·35	6·31	6·55	6·70	6·78	6·96		
	17/I, 1940	3·83	4·55	4·70	4·95	5·91	6·04	6·27	6·66	6·65		

The cold water in deeper layers on the banks in the coastal waters and within the fjords may be expected to be replaced (assuming a normal winter temperature in 1941). This hypothesis may be justified by the following reasoning: As the surface waters are subject to heating during the summer, the heat will be transmitted — by turbulence — to deeper layers and cause a certain heating also of the bottom water, which thus will lessen in weight; this water already being of lower salinity

1940 and 1941; it proves the layers below 75 m. still to have temperatures in 1941 below those prevailing in 1940 in the Vestfjord (see also Fig. 1), while the difference is less outside the Lofoten, where "normal conditions" as already mentioned are re-established, the temperature is slightly higher even in 1941 than in 1940.

[1]) In this case "normal" means "similar to conditions existing in a year immediately before the exchange took place".

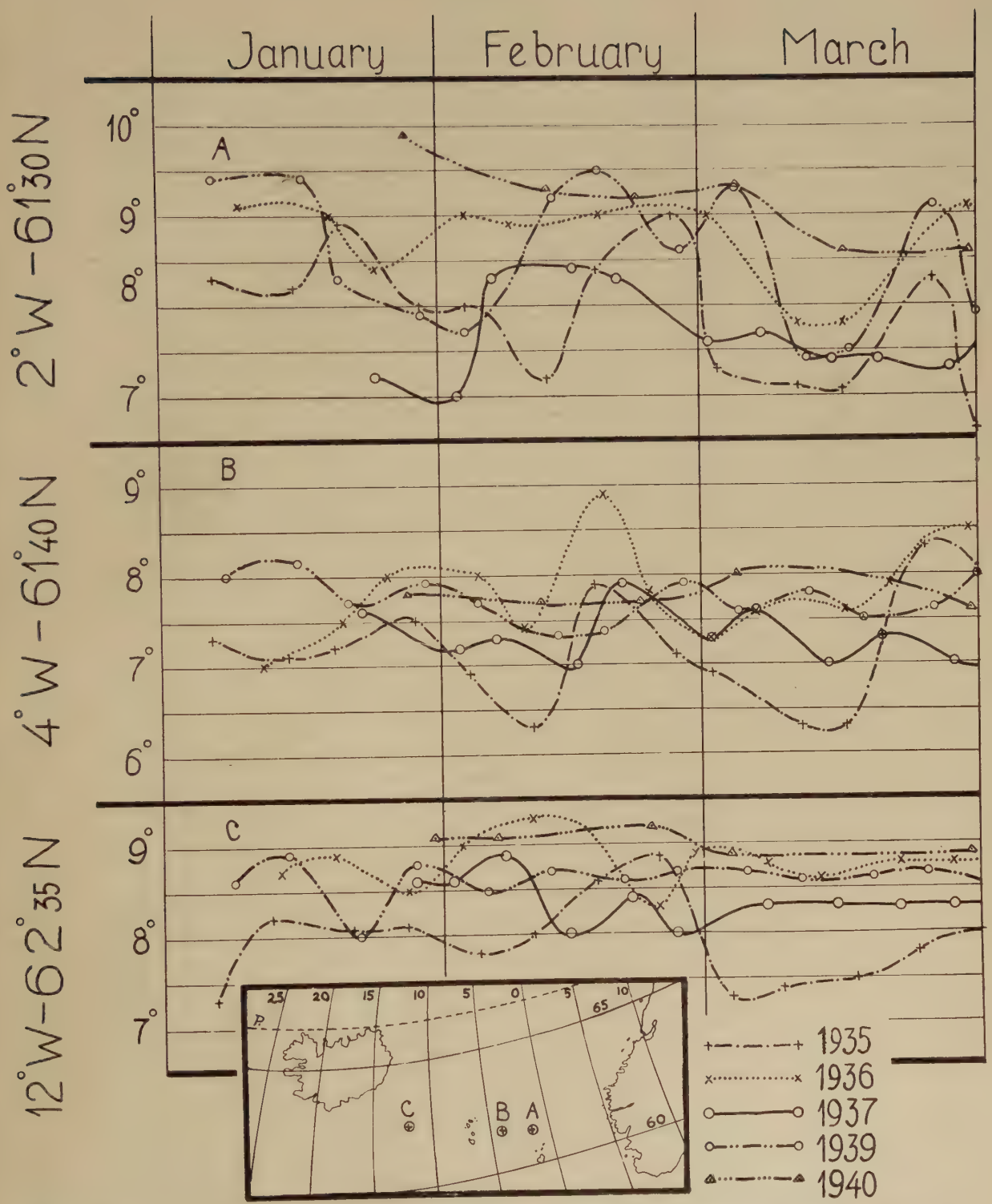


Fig. 10. Temperature at 4 m. depth in the Faroe—Shetland Channel (A and B) and between the Faroes and Iceland (C), during January to March, 1940, compared with the temperature during the same period in 1935—39.

The Working up of Sea-Surface Temperatures.

By

J. W. Sandström.

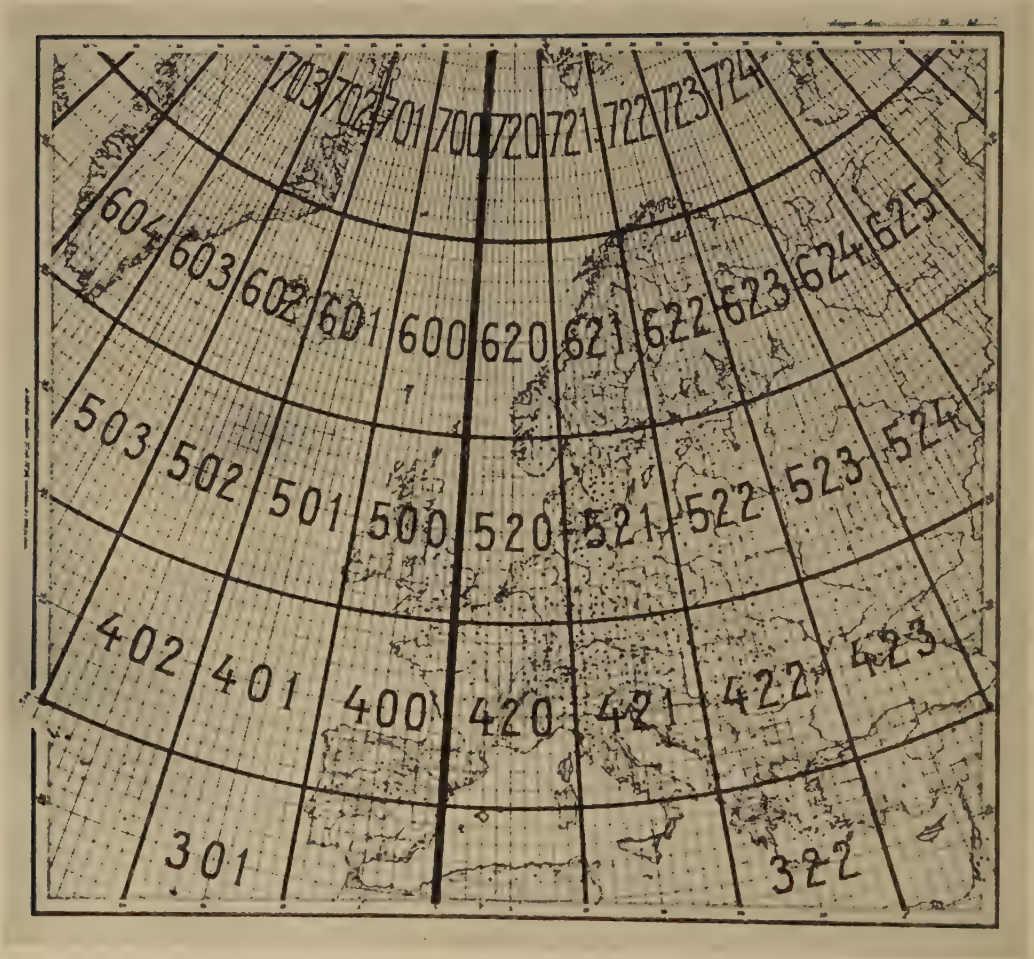


Fig. 1. Principal Squares.

1. Principal Squares.

THE task of working up the hydrographical observations taken from 1900 to 1935 was entrusted to me by the International Council for the Exploration of the Sea. The Administrative Secretary of the Council, Captain W. Nellemose, accordingly sent me a copy of the Hydrographical Card-Index in Copenhagen relating to the surface temperatures of the sea, calculated in monthly averages for rectangles of 1° of latitude by 1° of longitude as shown in table 1, which gives mean temperatures for the ten-year period 1920—1929 in the 1° square 49°N. 8°W., i.e., the rectangle bordered by the parallels 49°N. and 50° N. and by the meridians 8°W. and 9°W. I received 5291 such decade sheets, containing 105,837 mean temperatures based on 245,784 individually recorded temperatures of the sea surface. I have since included the temperature observations of the years 1936 and 1937 from the Bulletin Hydrographique, and my figures thus cover the whole period from 1900 to 1937. In dealing with this gigantic array of figures I have had the benefit of the kind assistance of Dr. K. A. Andersson, who has given me much good advice.

Working up so great a material the fractions — i.e., the minutes — of latitudes and longitudes must be omitted, and the grouping of the temperatures in 1° squares is thus very convenient. In fact all the mean temperatures given in table 1 are regarded as being located in the centre of the 1° square 49°N. 8°W., i.e., in the point 49°30′N. Lat. and 8°30′W. Long.

The designation of 1° squares may be considerably simplified by substituting for the letters N. and W. a cipher, for example 0. In the same manner the letters N-E. may in its quadrant of the earth be exchanged by the cipher 2, S-E. by 4, and S-W. by 6. This cipher is suitably placed between the figures denoting latitude and longitude; the 1° square 64°N. 37° W., for example, will accordingly be written 64037. In order always to obtain five-figure numbers, single-figure latitudes and longitudes are supplemented by a 0, 8°W. being for example written 08, making the 1° square 49°N. 8°W. in table 1, 49008. If the longitude exceeds 100°, the first figure 1 is added to the quadrant figure, making this odd instead of even. The 1° square 43°S. 125°W. will thus be designated 43725 (6 + 1 = 7), i.e., in this case, too, by a five-figure number.

Table 1.

Sea-Surface Temperatures from the International Hydrographical Card-Index in Copenhagen.

49°N. 8°W.

Period	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
1920						2 13.9	1 15.1						
1921	1 10.5						5 19.8	1 16.6			2 14.5		
1922			2 10.2	2 10.5		9 14.3		1 15.6					
1923					1 12.6	1 13.3	1 17.2	1 15.6					
1924	1 10.0	1 9.4	2 9.3		3 11.0	3 15.3					2 11.7		
1925		1 9.8			5 10.7			1 16.5			2 10.9		
1926		2 9.8	1 10.2		1 10.5			3 18.1			2 10.4		
1927		5 10.0			4 11.9			1 16.5					
1928				4 9.8	4 11.7		1 13.5	5 16.7				1 10.6	
1929	1 9.8				1 12.8	2 13.0		5 16.2	1 15.3	1 14.6	1 14.3	1 10.3	
A	3 10.1	9 9.9	5 9.8	6 10.0	19 11.4	17 14.2	8 18.1	18 16.6	1 15.3	1 14.6	9 12.1	2 10.4	95 13.2
B	3 10.1	4 9.8	3 9.9	2 10.2	7 11.6	5 14.0	4 16.4	8 16.5	1 15.3	1 14.6	5 12.4	2 10.4	12 12.6

Besides these 1° squares the Bulletin Hydrographique also uses larger squares bounded by 0°, 10°, 20°, 30°, etc. parallels and 0°, 10°, 20°, 30°, etc. meridians. These so-called "Marsden" squares thus comprise 100 1° squares. I have found the present designation of the Marsden squares inconvenient, however, and have therefore re-numbered them in conformity with the system described above for 1° squares, and propose for these re-numbered Marsden squares the name "Principal Squares". The principal square 60°N. 30°W. would then be designated 603, the principal square 40°S. 120°W. 472, and so on. To find the principal square in which a given locality is situated one has only to disregard all its latitude and longitude figures excepting those denoting tens of degrees. The 1° square 64°N. 37°W., for instance, is situated in the principal square 603, the 1° square 43°S. 125°W. in the principal square 472, and the 1° square 49°N. 8°W. of table 1 in the principal square 400. Fig. 1 shows some principal squares in the North Atlantic and its surroundings.

This superiority of the second method B may be explained by the following consideration: If many observations are taken in a given 1° square in the same month when the sea-water temperature is abnormally high or low, these abnormal values would become too heavily weighted if the number of actual observations were taken into account. All such observations are better regarded as one only, as is done in the second method, B.

Similar considerations apply to the resulting yearly means (13·2 and 12·6) in table 1. Since more observations are generally taken in the summer than at any other season, the summer temperatures would be too heavily weighted, i.e., the yearly means would be too high, if the number of observations were taken into account as in the method A in table 1. The yearly mean ought therefore to be calculated as the simple mean of the 12 monthly values, as in the method B. The figure 12·6 may therefore be regarded as the correct yearly mean temperature for the 1° square 49°N. 8°W. for the period 1920—1929. The figure 13·2, being too high, cannot be correct.

Table 2.

Decade Temperatures of the 1° Square.

49008 49°N. 8°W.

Period	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
1900-09	10.4	9.0	9.6	10.1	11.3	14.0	15.7	16.5	14.9	14.0	12.0	10.0	12.3
1910-19	9.5	9.7	9.4	10.0	11.7	15.6	14.4	17.4			12.4		
1920-20	10.1	9.8	9.9	10.2	11.6	14.0	16.4	16.5	15.3	14.6	12.4	10.4	12.6
1930-37	10.0	9.3	9.4	10.3	11.6	14.5	16.3	16.5	16.0	13.8	12.0	10.6	12.5
1900-37	10.0	9.4	9.6	10.2	11.6	14.5	15.7	16.7	15.4	14.1	12.2	10.3	12.5

2. Mean Temperatures.

The figures in table 1 are mean temperatures, their small indices indicating the actual number of temperature observations of which each is the mean. From these figures the mean temperatures of the whole decade can be calculated in two different ways: with or without taking into account the number of observations made. The results of the two operations, marked A and B respectively, are given at the bottom of table 1.

The relative merits of the two methods A and B may be open to discussion, but as the July value of +18·1 in table 1 fits in very badly between the June and August figures, +14·2 and +16·6 respectively, and a July value of +16·4 agrees much better with a June value of +14·0 and an August value of +16·5, the second method B appears to be the better. I have come to similar results in many other cases, and have since heard from my friend Mr. Oscar Sund that the Norwegians, too, have found the second method the better one.

The mean temperature of the 1° square 49008 for the whole period 1900—1937 can then be obtained by treating the other three decades in the same way (method B of table 1) and calculating the means of all the four decades as shown in table 2. This is the simplest way to get the means for the whole period when the decade means are known. But the results of this simplified method have to be compared with those of direct calculation as shown in table 3. There are differences, and as the method used for table 3 is correct, that method must be used for calculating the mean temperatures for the whole period.

The original material should therefore be arranged as in table 3. Such an arrangement has also other advantages. It gives a general view of all the material available from the 1° square in question, and provides moreover the only correct basis for a subsequent treatment of the figures. But its most important advantage is that the forms used for table 3 leave space for the statistical treatment of the figures in the table. At the bottom of the form I have provided twenty lines for that purpose.

Table 3.

Sea-Surface Temperatures of the 1° Square.

49008

49°N. 8°W.

Period	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
1900													
1901													
1902													
1903													
1904													
1905						[2] 14.1				[1] 13.3		[2] 10.9	
1906	[2] 10.0	[1] 9.4	[3] 10.9	[1] 10.0	[2] 10.0		[1] 14.4	[1] 16.7			[1] 10.0		
1907		[2] 8.9		[1] 11.1		[1] 14.4	[2] 16.7	[1] 15.6	[2] 14.2	[3] 13.1		[1] 7.8	
1908	[4] 9.5	[2] 8.0	[1] 8.5	[2] 9.2	[4] 11.8	[3] 13.8	[3] 16.4	[5] 17.1	[2] 15.2	[4] 14.8	[3] 13.5	[1] 12.2	
1909	[3] 11.6	[4] 9.9	[2] 9.4		[4] 12.0	[4] 13.8	[5] 15.2	[3] 16.6	[4] 15.2	[5] 14.6	[8] 12.5	[1] 10.0	
1910	[1] 9.5	[1] 9.5		[1] 10.1									
1911													
1912													
1913		[1] 10.6						[1] 17.8			[2] 12.2		
1914		[1] 8.9	[1] 9.4	[1] 10.0	[3] 11.7	[1] 16.1					[2] 12.5		
1915						[1] 15.0	[1] 14.4	[3] 16.9					
1916													
1917													
1918													
1919													
1920						[2] 13.9	[1] 15.1						
1921	[1] 10.5						[5] 19.8	[1] 16.6			[2] 14.5		
1922			[2] 10.2	[2] 10.5		[9] 14.3		[1] 15.6					
1923					[1] 12.6	[1] 13.3	[1] 17.2	[1] 15.6					
1924	[1] 10.0	[1] 9.4	[2] 9.3		[3] 11.0	[3] 15.3					[2] 11.7		
1925		[1] 9.8			[5] 10.7			[1] 16.5			[2] 10.9		
1926		[2] 9.8	[1] 10.2		[1] 10.5			[3] 18.1			[1] 10.4		
1927		[5] 10.0			[4] 11.9			[1] 16.5					
1928				[4] 9.8	[4] 11.7		[1] 13.5	[5] 16.7				[1] 10.6	
1929	[1] 9.8				[1] 12.8	[2] 13.0		[5] 16.2	[1] 15.3	[1] 14.6	[1] 14.3	[1] 10.3	
1930	[3] 10.0		[2] 9.2	[1] 10.0	[3] 11.9	[3] 14.7	[1] 16.2	[2] 15.7	[2] 15.0	[2] 12.3			
1931					[3] 11.5		[1] 15.4	[1] 15.2			[1] 11.7		
1932		[1] 9.5			[1] 10.9	[1] 13.3	[1] 16.0			[1] 14.7		[1] 10.2	
1933	[1] 9.3	[1] 7.9	[1] 9.6	[1] 10.1	[1] 11.7			[1] 18.4					
1934			[1] 10.7		[1] 11.2	[1] 14.3	[1] 17.8		[1] 14.3				
1935			[1] 8.2				[1] 16.6			[1] 13.4			
1936		[1] 9.6		[1] 10.5	[1] 12.3	[1] 14.6	[1] 16.4		[1] 17.0	[1] 14.6	[1] 12.2	[1] 10.6	
1937	[1] 10.6	[1] 10.3	[1] 9.5	[1] 10.6	[1] 11.8	[1] 15.4	[1] 16.0	[1] 16.8	[1] 17.6	[1] 14.2		[1] 11.1	
1938													
1939													
1900–1937	[10] 10.1	[15] 9.4	[12] 9.6	[11] 10.2	[18] 11.6	[16] 14.3	[16] 15.1	[18] 16.6	[8] 15.5	[10] 14.0	[12] 12.2	[9] 10.3	[12] 12.5

And for comparisons of the temperature figures in table 3 with the corresponding salinity and specific gravity values the latter values should be arranged in similar tables. Comparisons etc. can then easily be made by placing the tables of the several elements relating to the same 1° square side by side.

3. Monthly Charts.

Some charts showing the monthly mean surface temperature of the Atlantic Ocean already exist, but as I have not been able to find out how they are calculated they have been of little use to me. I have found that the original sea-surface temperatures have been smoothed to such an extent that many of their peculiar features have disappeared, and further that the calculated temperatures differ considerably from the observed temperatures. This was not a satisfactory basis for my investigations, and I have therefore re-made these monthly charts simply by putting into the 1° squares of the charts the actual mean temperatures obtained by the method of calculation shown in table 3. Warned by my experiences of the older charts, I have taken the greatest possible care to define in every particular how the figures in the new charts have been arrived at. Such a full and clear definition should be valuable to everybody who has to study the charts.

The figures in the charts often show irregularities due to peculiarities of the surface temperature. There are also irregularities which may be due to mistakes in the observations or to subsequent errors in the numerical treatment of the material. For example, the April temperatures of 62°N. 35°W. to 39°W. can scarcely be right, they are too high. But as I have not yet been able to decide if such divergencies are real or due to errors, and have furthermore been anxious not to reject any real oddities, I have retained them all.

The isotherms follow the figures and their irregularities as closely as possible. The irregularities have naturally given rise to many curlicues in the isotherms. These curlicues will have real significance if the corresponding irregular temperatures are true, but no significance if the underlying irregularity of temperature is due to an error.

The isotherms are well characterized by different drawing in order to facilitate their identification. Isotherms of 0°, 5°, 10°, 15° and 20° are drawn heavy, the thickness increasing with the temperature; isotherms of 1°, 6°, 11°, 16°, and 21° are made up of small circles; those of 2°, 7°, 12°, 17° etc. consist of short dashes; those of 3°, 8°, 13°, 18°, etc. of longer dashes; and finally isotherms of 4°, 9°, 14°, 19°, etc. of thin continuous lines. In this way every isotherm can be identified in spite of all its gambols.

Table 4.

Mean Sea-Surface Temperatures of 1° Squares in July 1908, extracted from the Bulletin Hydrographique.

65222	9.8	61219	13.8	59200	12.7	58206	14.6	54202	15.4	51203	16.8	57003	12.6
23	9.5	20	11.8	1	13.2	19	10.4	3	16.0	50200	15.0	56000	13.7
64221	8.7	21	13.4	19	14.9	20	13.6	4	15.4	1	14.8	1	13.3
22	7.9	60200	12.2	20	14.1	57200	13.6	5	16.2	61004	11.5	2	13.0
23	9.7	1	11.4	21	13.6	1	14.2	6	17.9	60001	11.8	54000	14.2
63219	11.5	2	11.6	22	13.8	2	14.1	53200	12.8	3	11.7	4	12.6
20	9.9	18	14.3	23	13.4	3	13.4	1	13.8	4	11.5	51004	15.0
21	9.3	19	15.7	24	16.4	19	11.3	2	14.5	59000	12.1	50000	14.7
62218	11.6	20	10.3	25	16.5	56200	14.8	3	15.2	1	13.5	1	14.6
19	11.0	21	12.9	26	16.8	1	14.6	4	16.0	3	11.1	3	14.2
20	9.6	22	11.7	27	16.5	2	15.2	6	16.1	4	13.9	4	17.0
61200	11.2	25	16.6	58200	13.2	3	14.4	52202	14.5	58000	12.5	49000	15.5
2	11.2	26	16.6	1	13.7	55203	14.8	3	14.7	1	12.0	2	14.9
3	9.4	27	17.0	2	13.5	4	14.8	4	16.4	2	11.4	3	14.4
17	13.7	28	18.2	3	13.8	54200	14.7	51201	15.9	3	13.1	4	17.2
18	13.9	29	18.1	4	13.7	1	14.3	2	15.6	57001	11.4	48002	15.4

4. Transcription of Hydrographic Records.

The mean surface temperatures sent to me from Copenhagen refer to the 1° squares west of longitude 5°W. In order to complete the monthly temperature charts east of that meridian I have used the Bulletin Hydrographique, beginning with July, 1908, and continuing with August, 1908, and so on for every single month of the whole period. But as the observations were published in the form of reports from the hydrographical expeditions this picking out of certain data was a very long and laborious job, which I have not yet been able to complete. The publication of these observations in the form of hydrographical reports is of very little use for scientific work, and I think this is the real reason why so little scientific use has so far been made of this valuable material — it is too inaccessible.

It has amused me to make some attempts at

transcribing the material into some form which is more suitable for scientific purposes. Time and space must be the ruling considerations in such a transcription. As only slow changes are under investigation in these cases, whole months provide sufficiently narrow time limits and 1° squares adequate space limits. One must thus first decide what month to study, and then ascertain the mean temperatures of that month in every 1° square where temperature observations are made. Table 4 shows such an arrangement for July, 1908, which is the sort of thing a scientist primarily needs. For later more detailed investigations he must go back to the Bulletin Hydrographique. But a similar arrangement — only with fuller particulars as to time and space — would be very useful there too. This has lately been realized by the editors of the Bulletin Hydrographique, and the improved manner in which this information is now given has made the recent annual volumes into a much better basis for scientific work than were the previous ones.

The numerous observations of sea-surface temperatures taken by merchant vessels should be collocated and published as in table 4, so as to provide material for monthly surface temperature charts of all seas.

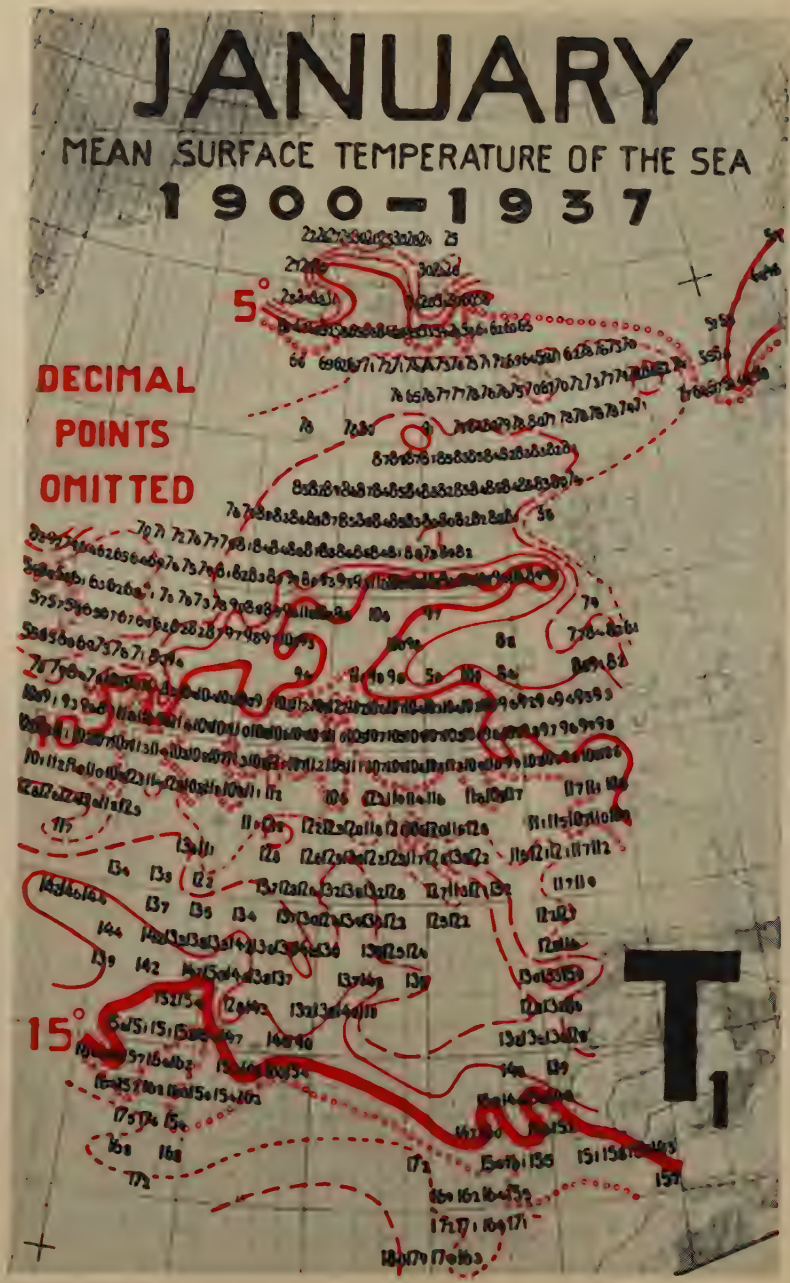
Some improvements would have made the figures in the appended charts still better suited for scientific treatment. They ought to have been corrected to the centres of the 1° squares and to the middle of the months. If, for instance, in a spring or autumn-month the figure in a 1° square should refer to the beginning of the month, and the figure in the neighbouring square to the end of the same month, this difference in time will cause a difference in temperature which may disturb the significance of the chart. These inconvenient differences may cause meaningless numerical irregularities, and the corresponding gambols of the isothermal lines thus greatly disturb any investigations. The correction of the sea-surface temperatures in the way suggested will leave a limited number of equidistant points to which the observations are referred, and will give a very clear picture of the conditions, which will greatly facilitate the work. Table 4 would then contain these corrected values; for instance, the figures 65222 98 would signify that on the 15th of July, 1908, the surface temperature at the point 65°30′ N. 22°30′ E. was + 9·8°.

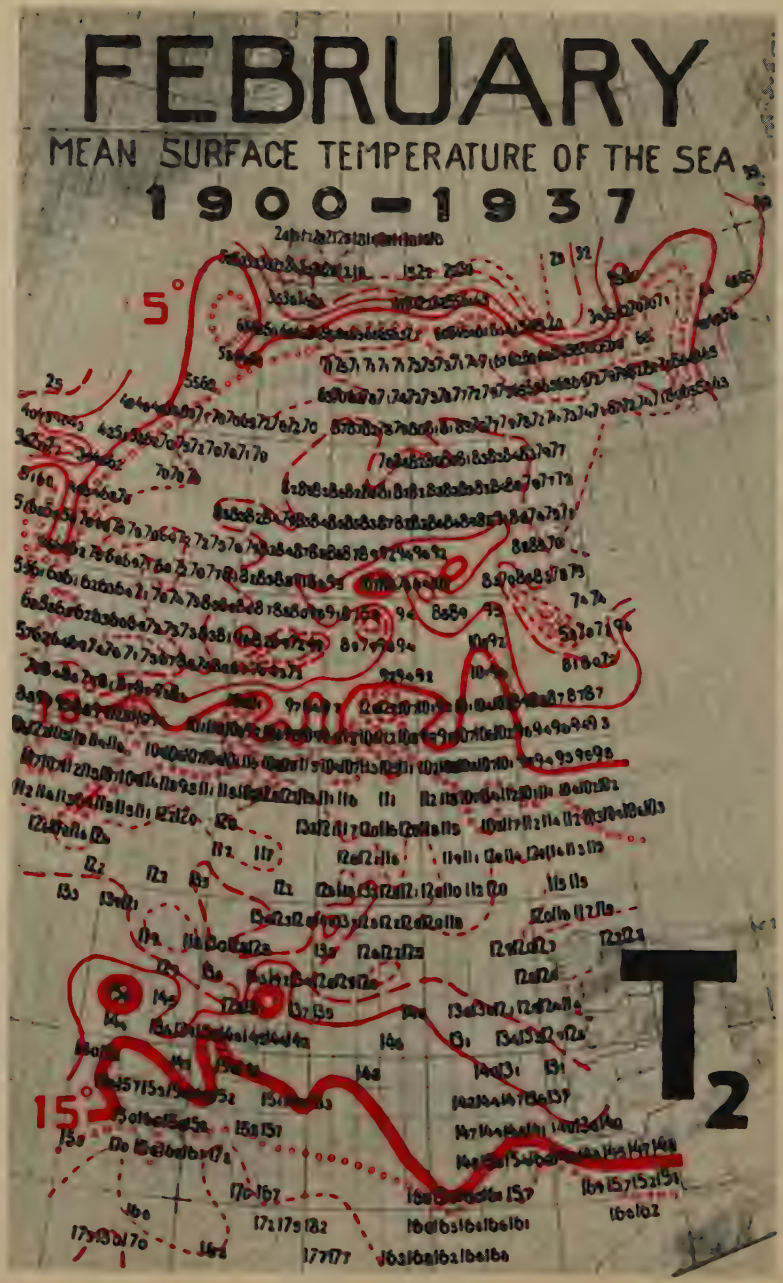
Since 1932, the hydrographical observations have been published in a manner that is well suited for scientific treatment. The manner of publication would, however, be still more improved if the material were arranged by months, so that the annual volumes would begin with all observations taken in January, followed in the next section by the observations taken in February, and so on. Such an arrangement would facilitate all the numerous primary investigations referring to a given time, which will always be the principal object of study.

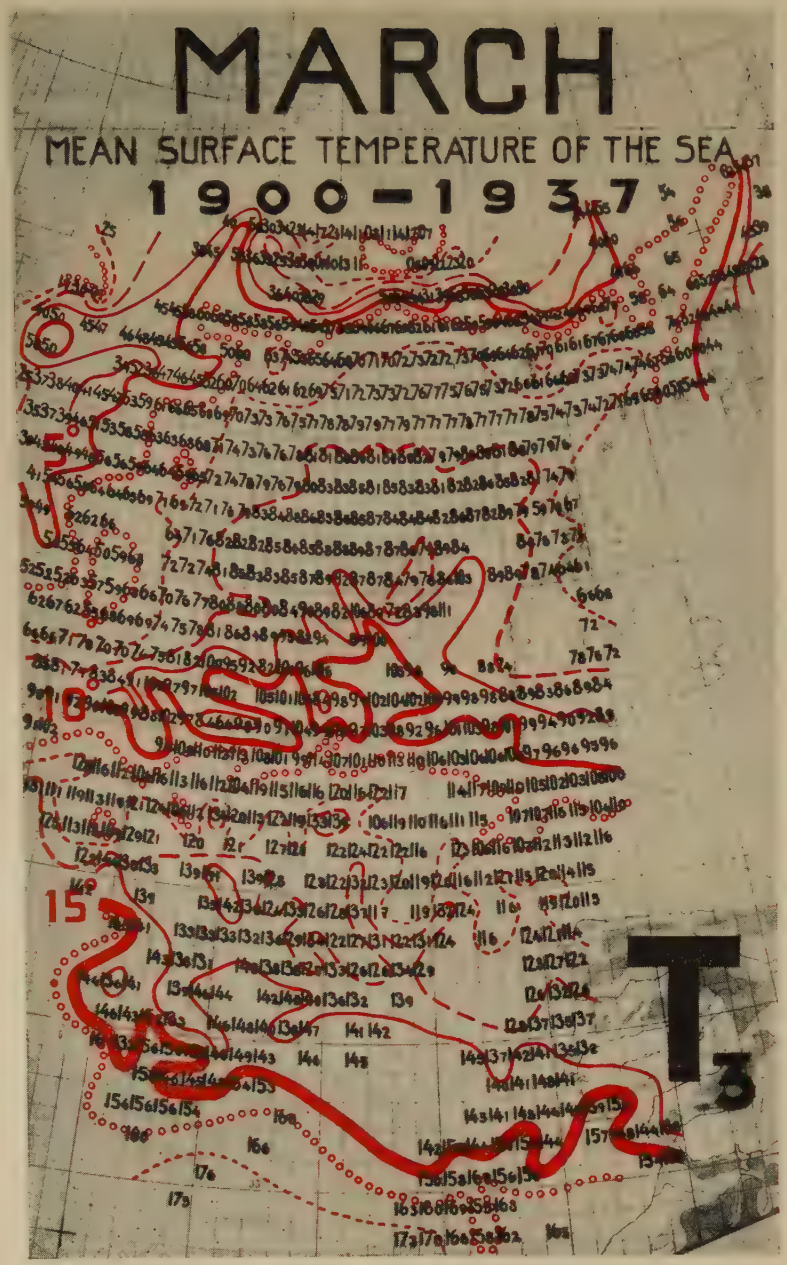
5. Conclusions.

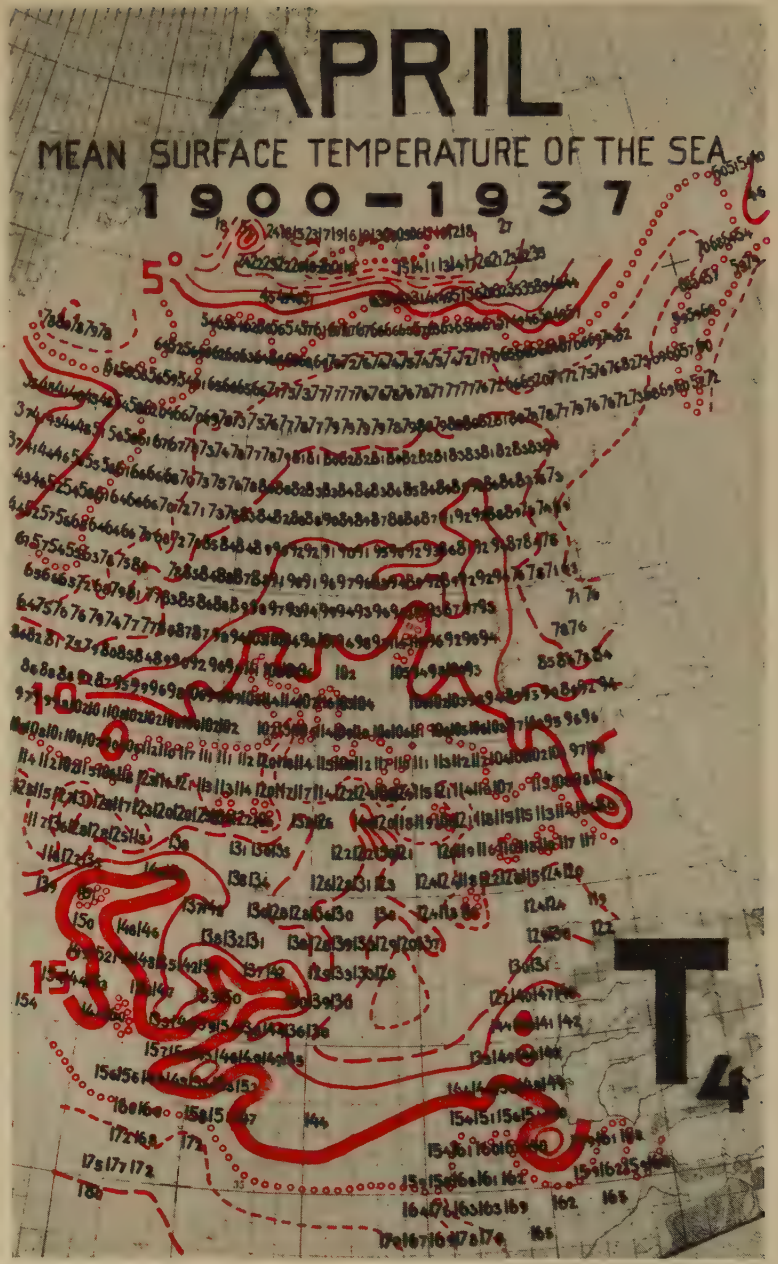
The mean temperatures calculated as shown in table 3 might of course have been published in a huge but not very perspicuous table. However, in order to give life to the dry figures I have preferred to place them in their appropriate 1° squares in 12 charts — one for each month of the year — and to draw the corresponding very characteristic isotherms. That arrangement facilitates the use of the figures for further investigations of sea surface temperatures. Some interesting facts emerge at first glance: the great length of the winter, April being one of the coldest months of the year; the northward progress of summer in June, July, and August, and its return south in October and November; the great homogeneity of the water of the Gulf Stream, while the waters south of the Gulf Stream and near the coast are very heterogeneous; the rapid fall of the temperature towards Greenland; and many other peculiarities well worth a closer study. All such peculiarities are made more or less apparent by this lucid method of representation.

But the chief importance of the figures given in the monthly charts is that they constitute a reliable foundation for further statistical investigations. My next task will be to use them for constructing seasonal charts of mean sea-surface temperatures.

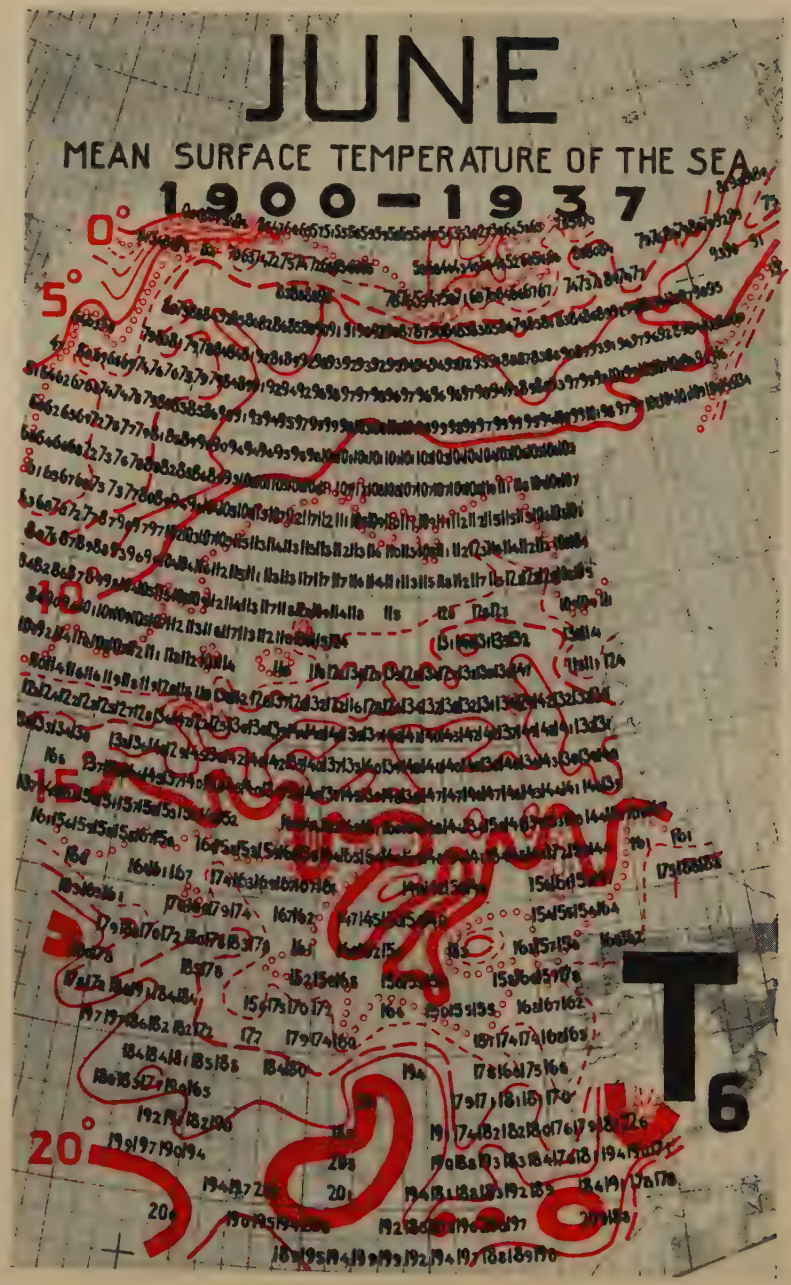

JANUARY
MEAN SURFACE TEMPERATURE OF THE SEA
1900—1937
DECIMAL POINTS OMITTED
5°
10°
15°
T1

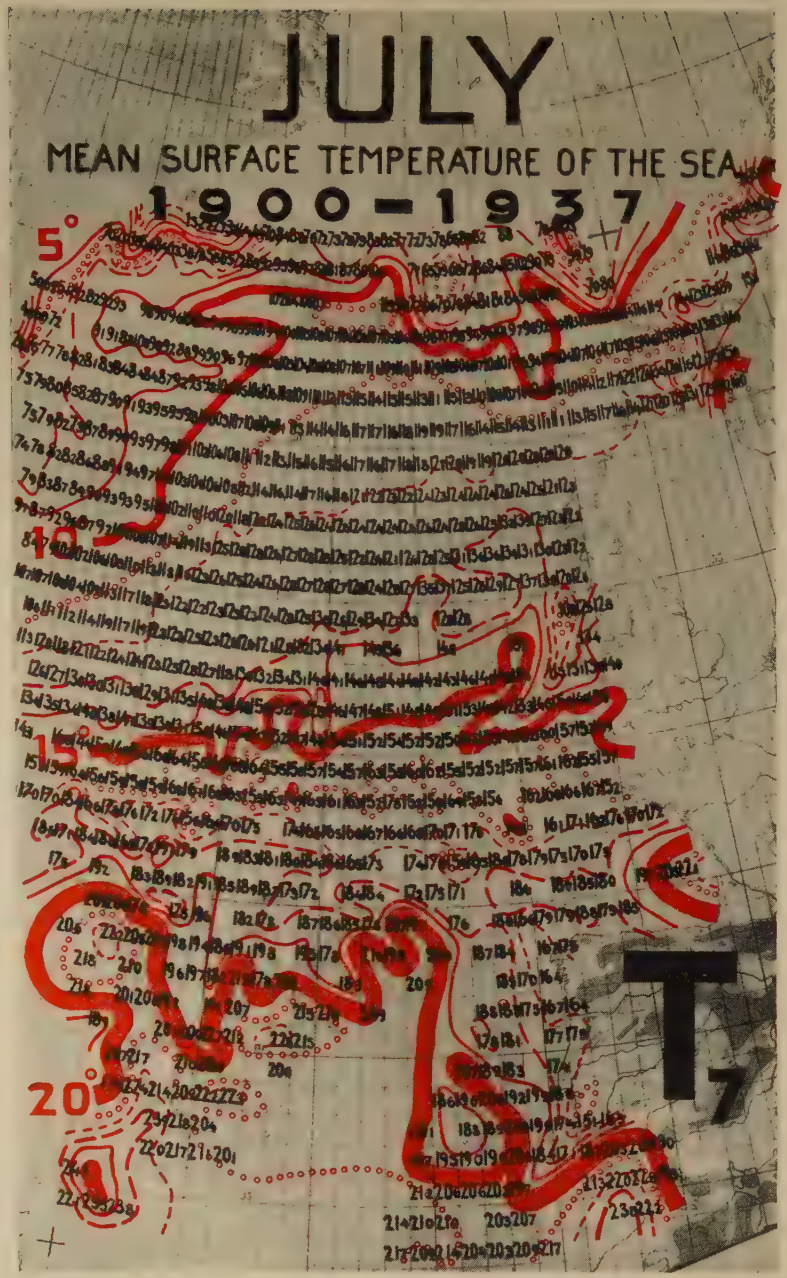

FEBRUARY
MEAN SURFACE TEMPERATURE OF THE SEA
1900—1937
5°
10°
15°
T2


MARCH
MEAN SURFACE TEMPERATURE OF THE SEA
1900–1937
T3

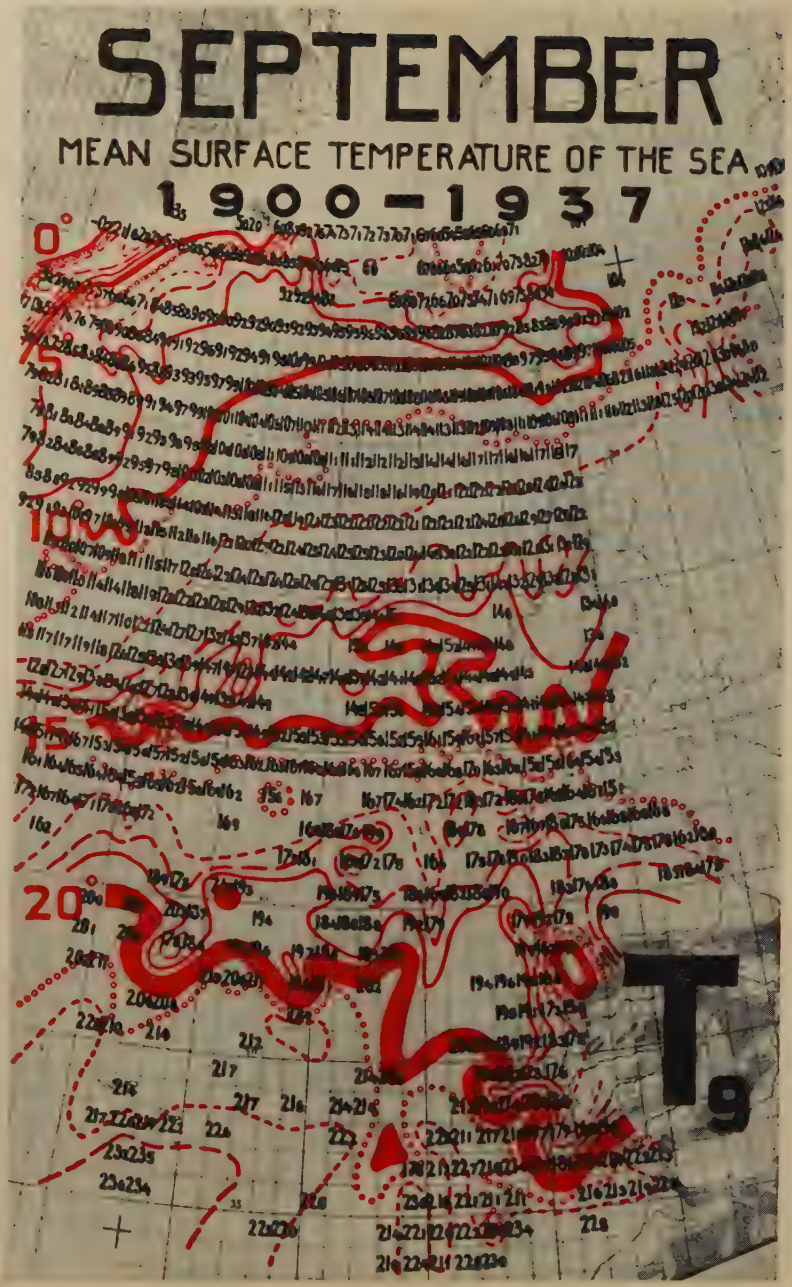

APRIL
MEAN SURFACE TEMPERATURE OF THE SEA
1900–1937
T4

MAY
MEAN SURFACE TEMPERATURE OF THE SEA
1900–1937
5°
15
T5

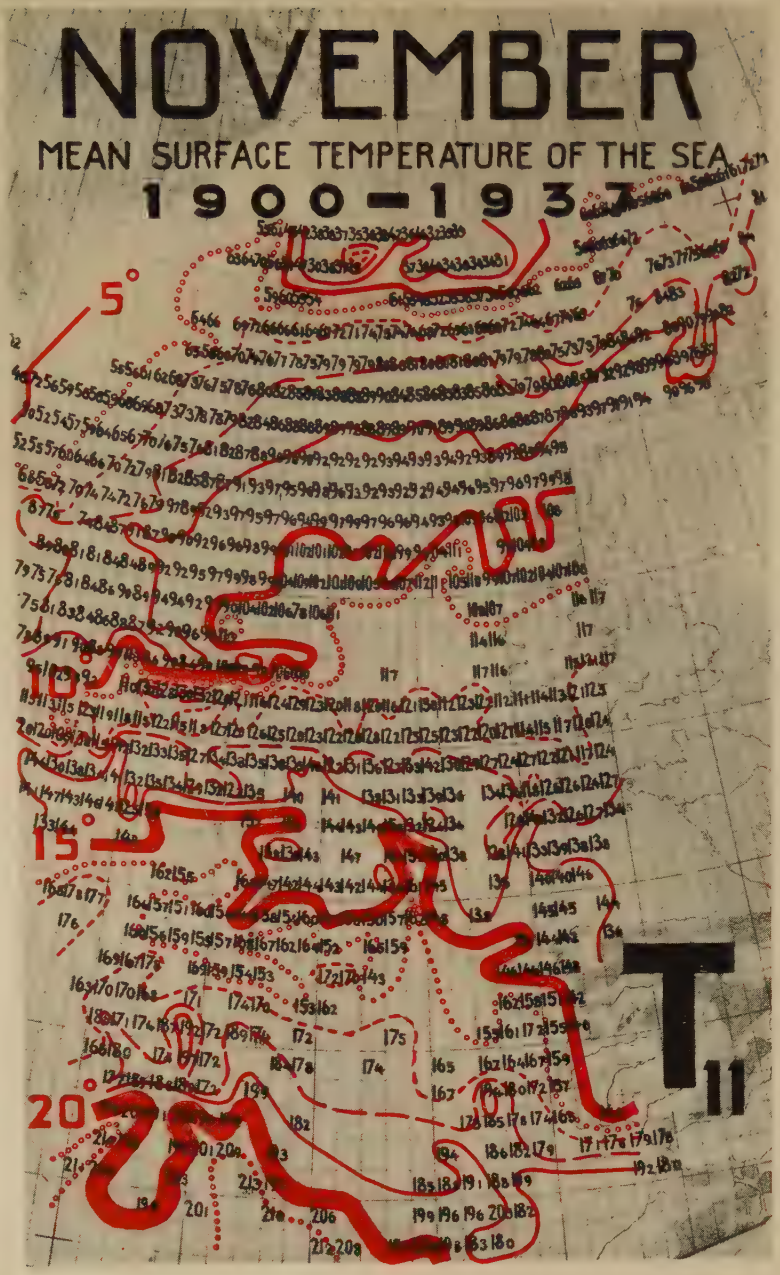

JUNE
MEAN SURFACE TEMPERATURE OF THE SEA
1900–1937
0°
5°
10
15
20°
T6

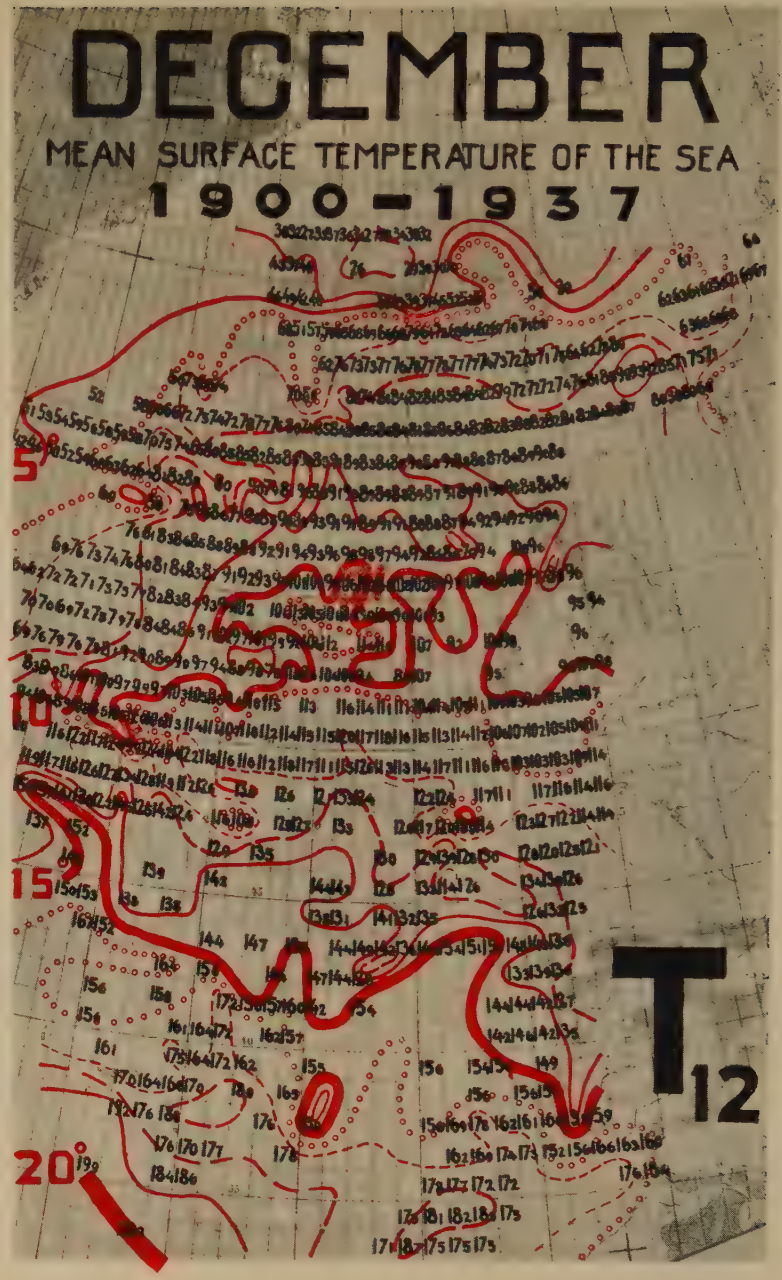

JULY
MEAN SURFACE TEMPERATURE OF THE SEA
1900-1937
5°
10°
15°
20°
T 7

AUGUST
MEAN SURFACE TEMPERATURE OF THE SEA
1900-1937
0°
5°
10°
15°
20°
T 8


SEPTEMBER
MEAN SURFACE TEMPERATURE OF THE SEA
1900-1937
0°
5°
10°
15°
20°
T9

OCTOBER
MEAN SURFACE TEMPERATURE OF THE SEA
1900-1937
5°
10°
15°
20°
T10


NOVEMBER
MEAN SURFACE TEMPERATURE OF THE SEA
1900—1937
5°
10°
15°
20°
T11


DECEMBER
MEAN SURFACE TEMPERATURE OF THE SEA
1900—1937
5°
10°
15°
20°
T12

Annual and Seasonal Variations in the Salinity of the North Atlantic Surface Water.

By

Jens Smed.

VARIOUS investigations (Scherhag 1937) have proved that for a series of years — ever since 1920 in fact — the temperature of the surface water over wide areas of the northern Atlantic and Arctic waters has been subject to a considerable increase. Scherhag (1936) has shown that simultaneously an increase of the atmospheric circulation took place, and it is natural — with Scherhag — to expect some connexion between the two phenomena. Thus it seems reasonable to assume that the increased atmospheric circulation might cause certain geographical displacements of the water masses and especially so that the influence of the Atlantic water with high temperature and salinity was increased in the northern areas. The increased atmospheric circulation may also account for an increase of the air temperature in the northern areas and thus — due to the exchange of heat between air and water — for an increase in the temperature of the surface water in these areas. At the same time, the increased atmospheric circulation would intensify the evaporation of the surface water and thereby cause an increase in its salinity. From the stated suppositions it is thus to be expected that an increase in surface temperature must be followed by an increase in the salinity. In fact this has also been found to be the case at several places in the Arctic waters and in the Norwegian Sea (see Ad. S. Jensen, 1939, p. 57). Furthermore, Defant and Helland-Hansen (1939) have compared temperatures and salinities in a section taken in 1938 from the English Channel to the Azores with those recorded in the same section taken in 1914; at all depths the 1938-values were higher than those of 1914.

It would be of interest then to examine the changes in the salinity of more extensive areas. Surface observations only are available in numbers sufficient for any useful examination — and even such material exists for limited areas only. The material used is that of the Card-Index of the International Council, practically comprising all salinity observations published since 1902 from the northern Atlantic.

The investigations mentioned above all point towards the probability of the increase in salinity having commenced about 1920. All observations within each 1°-square were, therefore, arranged in two groups, the one containing those from 1902—17, the other one covering the period 1919—39. This arrangement was natural also from another point of view, viz., that material was very scarce during the last couple of years of the War (1914—1918). Mean values for the 1°-squares were calculated for each month throughout the entire period (1902—1939), and from these the mean value for the summer (May—October) and the winter (November—April) was calculated for each of the two main periods. Finally, 5°-square means were calculated from the 1°-square means. In Figs. 1—4, the 5°-square means are recorded within the corresponding squares and below each of these values the number of observations used for its calculation has been recorded. Differences between the values recorded in Figs. 1 and 3 and between those recorded in Figs. 2 and 4 thus give — for summer and winter respectively — the variation in salinity from the period of 1902—1917 to that of 1919—1939. Considering, however, that the distribution of the observations within each 5°-square is different in the two periods, a more exact picture of the variation is probably obtained by calculating differences between salinities within each 1°-square and then forming mean differences for the 5°-squares. In adopting this method we arrive at the figures recorded in Figs. 5 and 6 for summer and winter respectively. These latter figures record the increase in salinity — with 0.01 ‰ as unit — from the 1902—1917 period to the 1919—1939 one. The figures show that the increase in surface salinity over the major part of the areas examined amounts to about 0·10 ‰ or slightly less. In the south-eastern corner of the area — the waters off the Iberian peninsula — a corresponding *decrease* in salinity will be noticed.

For investigations like those just discussed it would have been a great advantage to have at our disposal observations at fixed stations, continuously repeated during both the periods. Approximately fixed stations of this kind exist in the Faroe—Shetland Channel, and in the left-hand part of table 1 means of surface salinities observed are recorded for a series of such fixed stations for the April and July quarters within the two periods (1902—

Fig. 1.

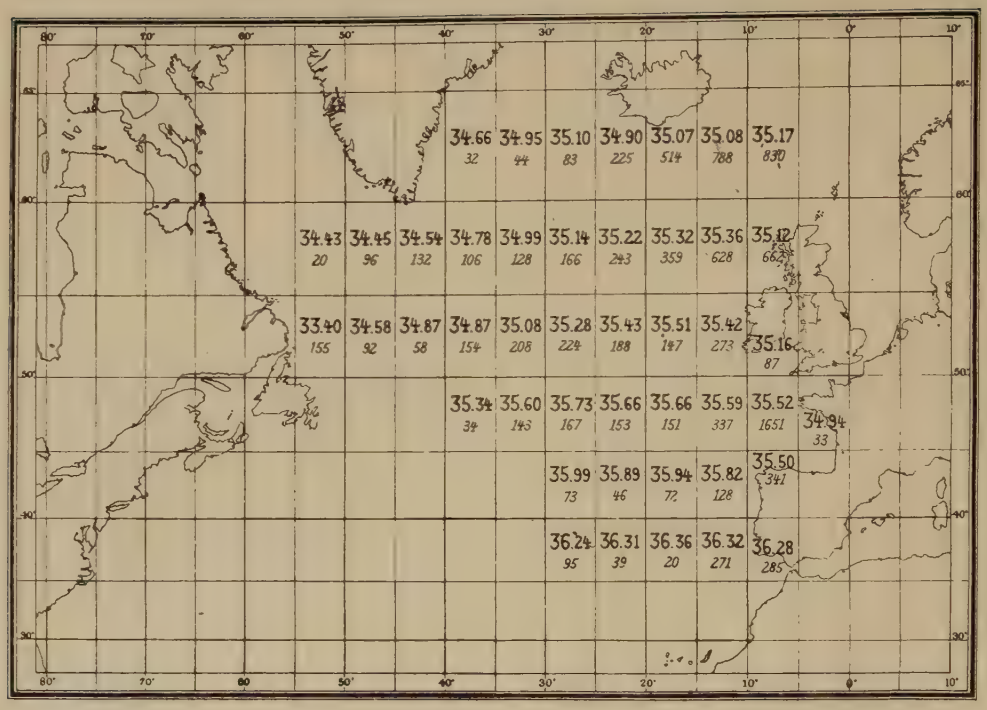
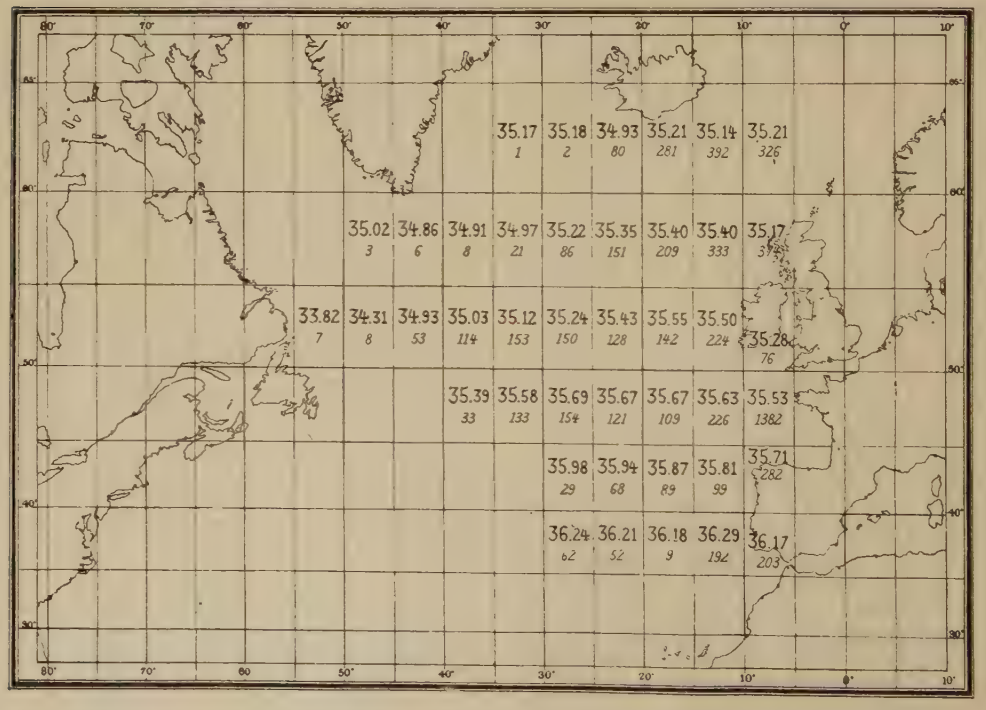


Fig. 2.



Figs. 1 and 2. Mean surface salinity during the summers 1902—1917 (Fig. 1) and the winters 1902—1917 (Fig. 2). Below each mean is recorded the number of observations on which it is based.

Fig. 3.

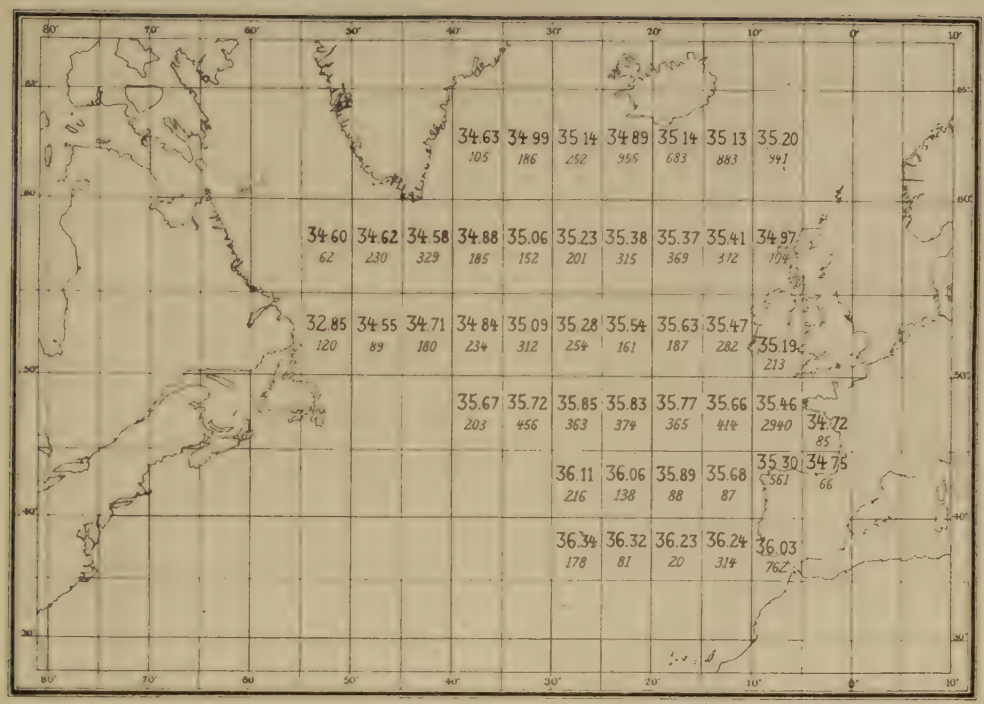
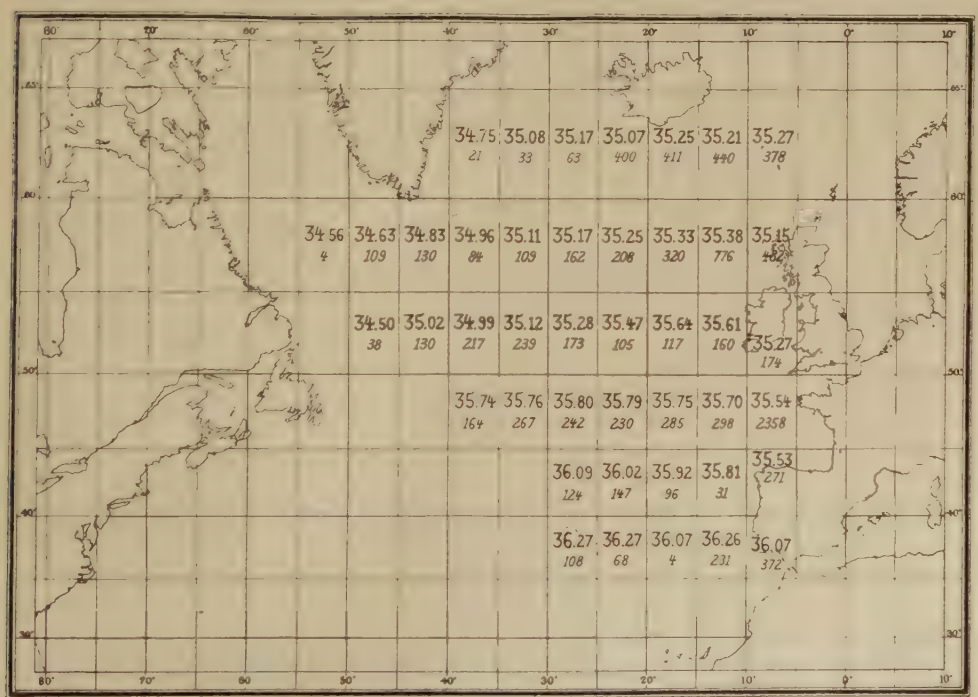


Fig. 4.



Figs. 3 and 4. Mean surface salinity during the summers 1919—1939 (Fig. 3) and the winters 1919—1939 (Fig. 4). Below each mean is recorded the number of observations on which it is based.

1917 and 1919—1939) ; the index figures record the number of observations used for calculation of the means. From these station-means the mean values for all stations, as recorded in table 1, were calculated. The increase in the surface salinity from the earlier to the later period was 0.08 $^0/_{00}$. — The material from these stations may furthermore be used for investigating the variation of the salinity in deeper layers. Means for 200 m. depth were, therefore, calculated like those for the surface and are recorded in the right-hand part of Tab. 1. With regard to stations Sc 16A and Sc 16, where the depth is less than 200 m., the 100 m.-values are recorded. Mean values for all the stations are recorded in table 1 and show the increase of the salinity at 200 m. to be 0·08 $^0/_{00}$, i.e., the same increase as for the surface.

The increase of salinity from the period 1902—1917 to the period 1919—1939 may thus be accepted as unquestionable. Certain areas are so well covered by observations that the variation can be followed year by year; such areas are marked A, B, C, D, E, F, and G in Fig. 7 and their limits recorded in Tab. 2. It was assumed that the salinity S within each area varies linearly with latitude and longitude, thus:

$$S = a + bx + cy$$

where x and y indicate deviation of latitude and longitude from the centre of the area, while a, b and c are constants indicating the salinity at the centre (a) and the gradients of salinity (b and c) according to latitude and longitude. From the four sets of mean values (summer and winter, 1902—1917 and 1919—1939) for the 1°-squares within an area A, B, ... G, four sets of constants (a, b, c) were calculated by the method of least squares.

The four values of a indicating the mean salinity at the centre of an area are recorded in Tab. 2 for the areas in question. Furthermore the increase of the salinity from 1902—1917 to 1919—1939 for summer and winter is recorded in the table, and the values show a fairly satisfactory accordance with the values in Figs. 5 and 6.

By means of the salinity gradients b and c the single observations within an area A, B, ... G were reduced to the centre of the area and means of the reduced observations were computed for summer and winter in the single years. These means are plotted in Figs. 8A, 8B, ... 8G for the areas A, B, ... G, and on the basis of the plotted points, curves are drawn on estimate.

The reliability of the variation of the salinity year by year as shown in Figs. 8A, 8B, ... 8G was controlled in the following way. Referring to each of the areas A, B, ... G for summer and winter respectively, the standard error σ_1 for the salinity as given by the reduced observations was calculated under the supposition that the deviations from the general mean for all the years were normally distributed. The values obtained for the standard error σ_1 are stated in Tab. 3. Supposing the

Table 1.
Salinity (in per mille) at Different Hydrographic Stations in the Faroe—Shetland Channel.

		0 m.		200 m. (* 100 m.)	
		April-May-June	July-Aug.-Sept.	April-May-June	July-Aug.-Sept.
Sc 13 A	1902—17	$35\cdot34_{11}$	$35\cdot29_{8}$	$35\cdot27_{11}$	$35\cdot26_{8}$
	1919—39	$35\cdot40_{7}$	$35\cdot38_{2}$	$35\cdot36_{7}$	$35\cdot39_{2}$
Sc 14 A	1902—17	$35\cdot30_{10}$	$35\cdot17_{7}$	$35\cdot22_{10}$	$35\cdot16_{7}$
	1919—39	$35\cdot38_{7}$	$35\cdot30_{2}$	$35\cdot29_{7}$	$35\cdot26_{2}$
Sc 15 A	1902—17	$35\cdot28_{10}$	$35\cdot17_{7}$	$35\cdot14_{10}$	$35\cdot15_{7}$
	1919—39	$35\cdot34_{7}$	$35\cdot16_{2}$	$35\cdot26_{7}$	$35\cdot12_{2}$
Sc 15 B	1902—17	$35\cdot23_{11}$	$35\cdot17_{8}$	$35\cdot19_{10}$	$35\cdot20_{8}$
	1919—39	$35\cdot29_{7}$	$35\cdot30_{2}$	$35\cdot26_{7}$	$35\cdot28_{2}$
Sc 16 A	1902—17	$35\cdot20_{10}$	$35\cdot19_{7}$	$35\cdot18_{10}$*	$35\cdot20_{7}$*
	1919—39	$35\cdot26_{7}$	$35\cdot27_{2}$	$35\cdot26_{7}$*	$35\cdot30_{2}$*
Sc 16	1902—17	$35\cdot20_{11}$	$35\cdot17_{8}$	$35\cdot18_{10}$*	$35\cdot16_{8}$*
	1919—39	$35\cdot28_{7}$	$35\cdot28_{2}$	$35\cdot27_{5}$*	$35\cdot26_{2}$*
Mean Values for all Stations	1902—17	$35\cdot26_{63}$	$35\cdot19_{45}$	$35\cdot20_{61}$	$35\cdot19_{45}$
	1919—39	$35\cdot33_{42}$	$35\cdot28_{12}$	$35\cdot28_{40}$	$35\cdot27_{12}$
Increase		0·07	0·09	0·08	0·08

Fig. 5.

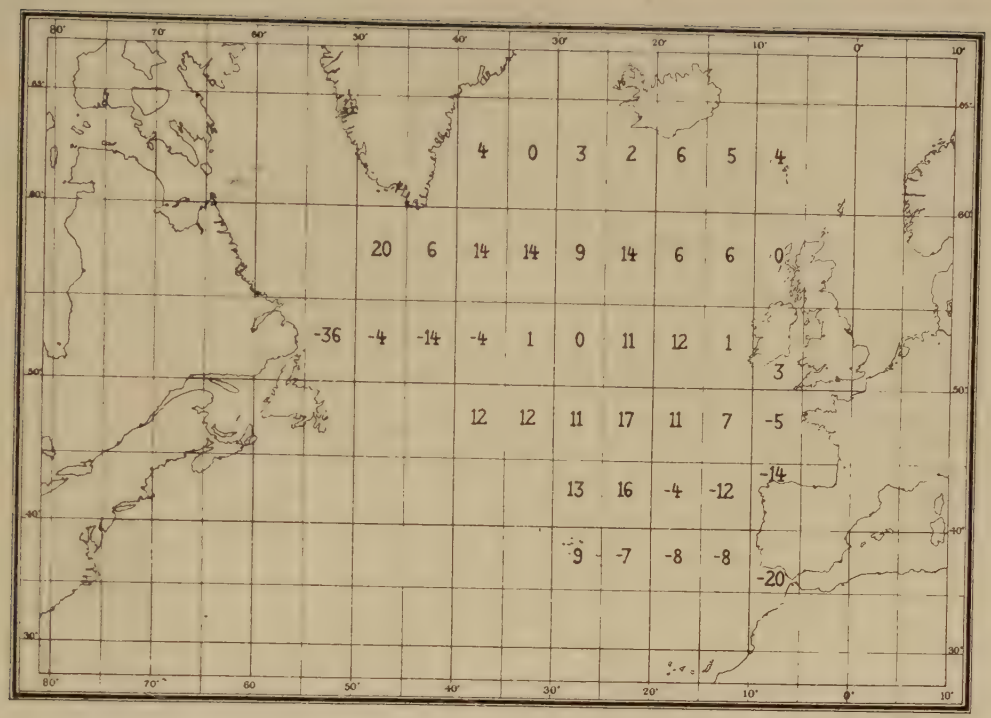
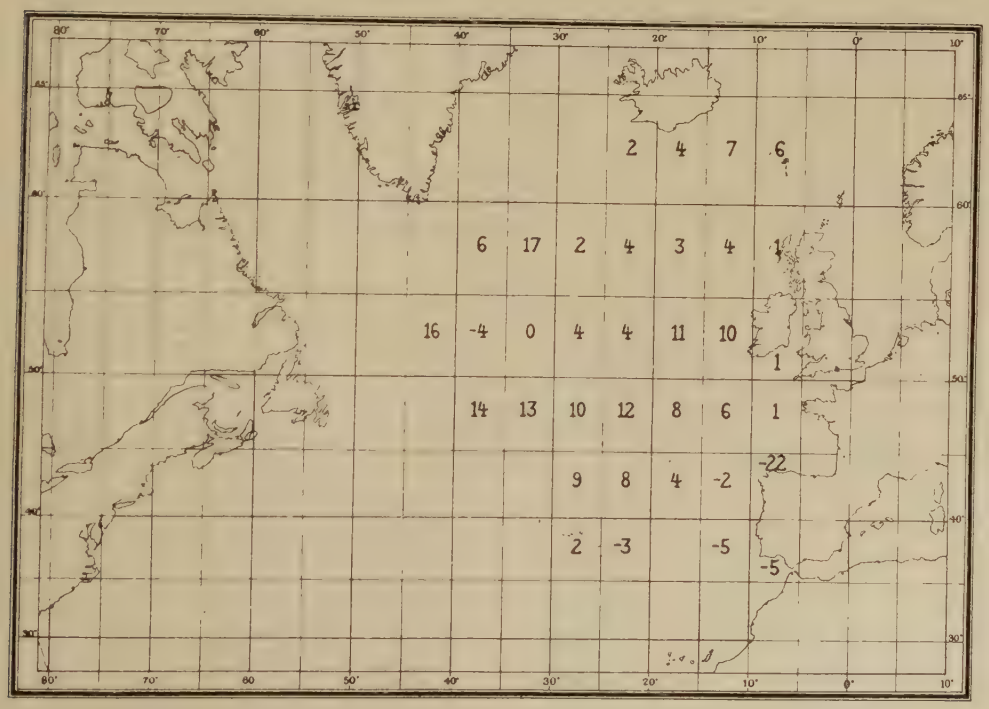


Fig. 6.



Figs. 5 and 6. Increase of surface salinity — in 0·01 units — from the period 1902—1917 to the period 1919—1939. Summer (Fig. 5) and winter (Fig. 6).

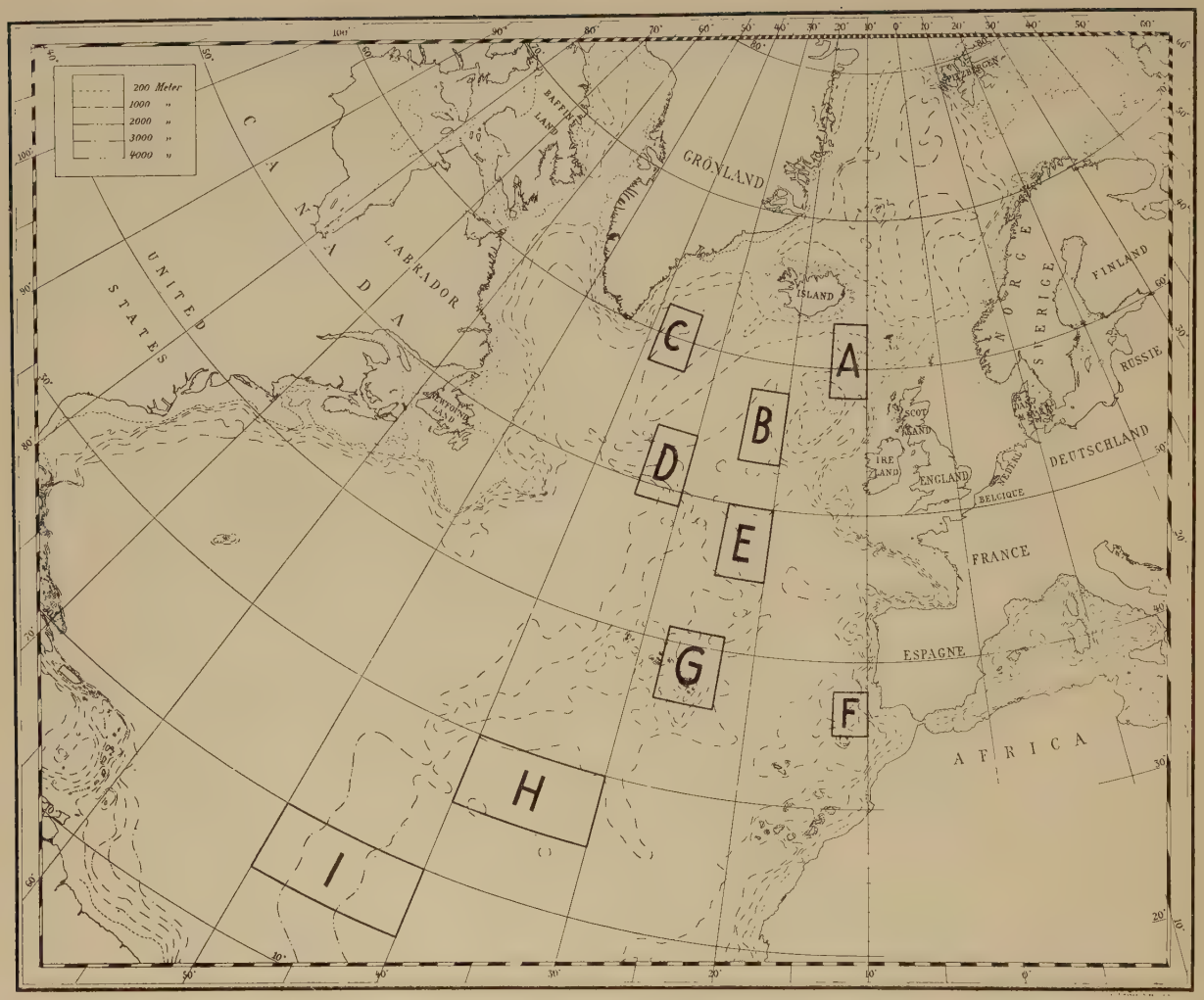


Fig. 7.

systematic variation of the salinity shown by the curves in Fig. 8 to be a reality, a value σ_2 for the standard error was calculated as follows. For the different years the differences between the values of the salinity as given by the reduced observations and the values of the salinity as shown by the curves were found. For each of the areas A, B, ... G for summer and winter respectively, the standard error σ_2 was calculated on the basis of the said differences. The values found for σ_2 are recorded in table 3. Now the reciprocal values of the squares σ_1^2 and σ_2^2 may be taken as measuring the goodness of the two hypotheses (1) that the salinity in an area, summer or winter, should be constant, and (2) that it should vary according to the respective curve. It is seen from table 3 that the values of σ_1^2/σ_2^2 for most of the areas are essentially greater than 1. Furthermore, the fact that the main features of the curves in Fig. 8 are in most cases the same, strengthens the trustworthiness of the supposed variation of the salinity.

On the basis of the σ_2-values the standard error of each of the mean values plotted in Fig. 8 was found and given in the figure by half the length of the vertical line through the point. In several cases the curves fit very well to the points, so that the distance from the curve to a plotted point does not exceed two or three times the standard error. In some other cases the accordance between the actual values and the supposed variation cannot be taken as significant. On the whole, the reality of the supposed variation can, however, scarcely be questioned.

An examination of the curves in Fig. 8 shows that the salinity — for the areas A—E — ordinarily decreases to a minimum in the first half of the period considered. The time at which this minimum is reached is rather uncertain, which partially may

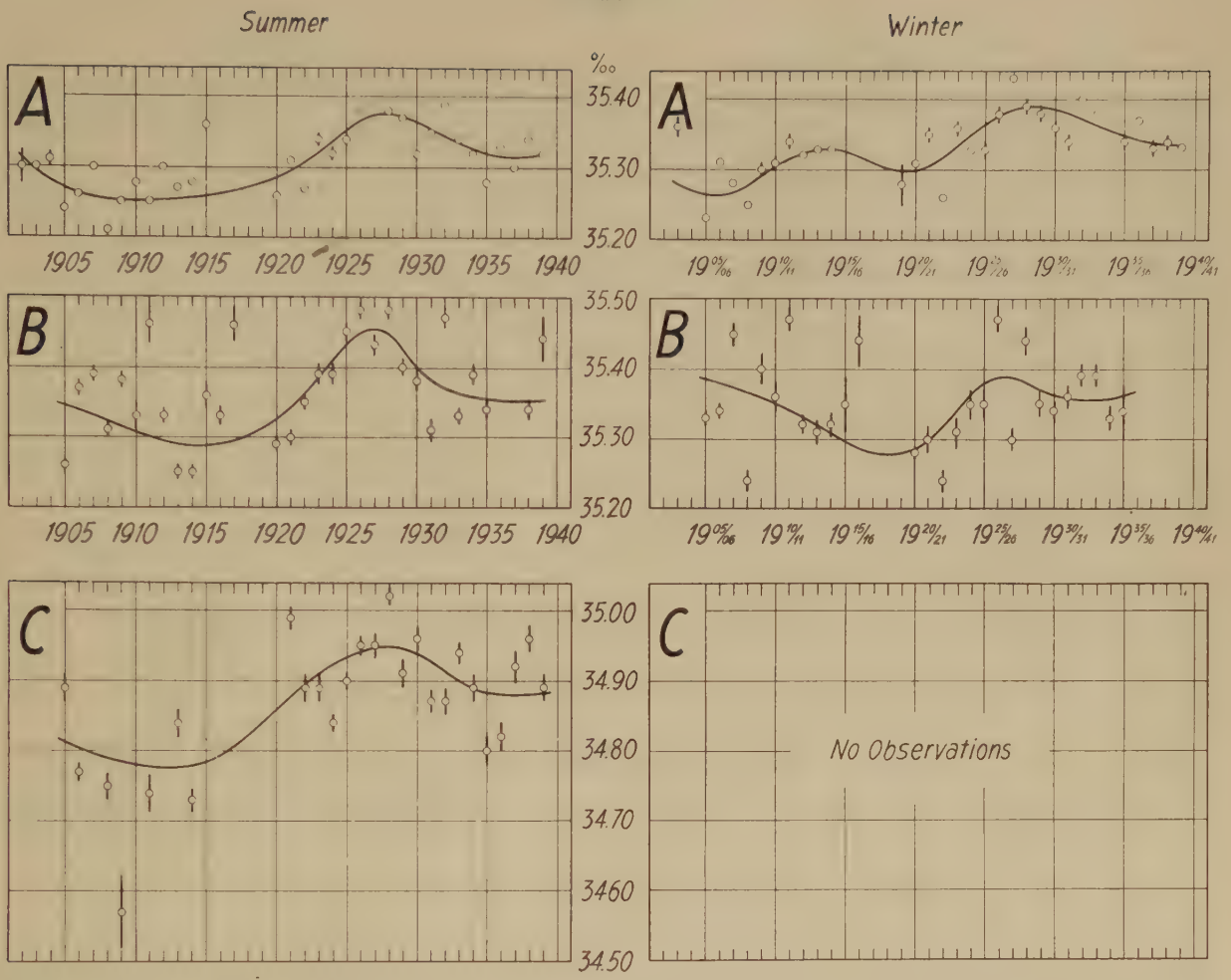


Fig. 8 A, B, C. Variation of surface salinity from year to year in the areas A, B and C (see Fig. 7). The standard error of the mean represented by a point is given by half the length of the vertical line through the point. Where no standard error is indicated, it does not exceed the radius in the circle marking the point.

Table 2.
Surface Salinity (in per mille) at the Centres of Various Areas of the Northern Atlantic.

	Area	Summer (May—October) 1902—1917	1919—1939	Increase	Winter (November—April) 1902—1917	1919—1939	Increase
A	58°N.—63°N. 10°W.—15°W.	35·26	35·34	0·08	35·30	35·35	0·05
B	53°N.—58°N. 20°W.—25°W.	35·33	35·37	0·04	35·35	35·34	—0·01
C	58°N.—62°N. 34°W.—39°W.	34·79	34·92	0·13	—	—	—
D	49°N.—54°N. 30°W.—35°W.	35·14	35·15	0·01	35·23	35·19	—0·04
E	45°N.—50°N. 20°W.—25°W.	35·67	35·83	0·16	35·67	35·78	0·11
F	35°N.—38°N. 10°W.—13°W.	36·48	36·34	—0·14	36·43	36·30	—0·13
G	36°N.—41°N. 23°W.—28°W.	36·22	36·23	0·01	36·19	36·21	0·02

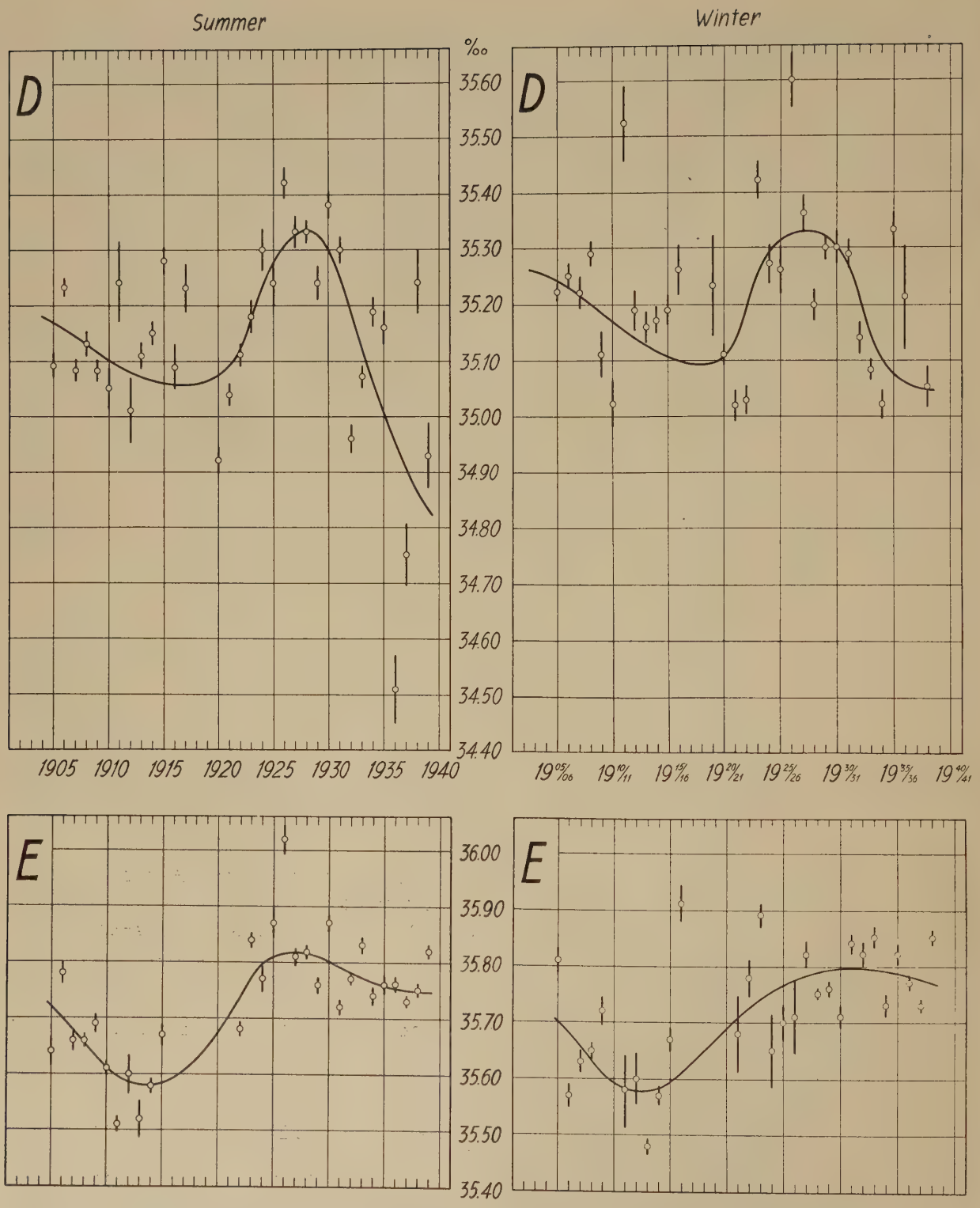


Fig. 8 D, E. Variation of surface salinity from year to year in the areas D and E (see Fig. 7). The standard error of the mean represented by a point is given by half the length of the vertical line through the point.

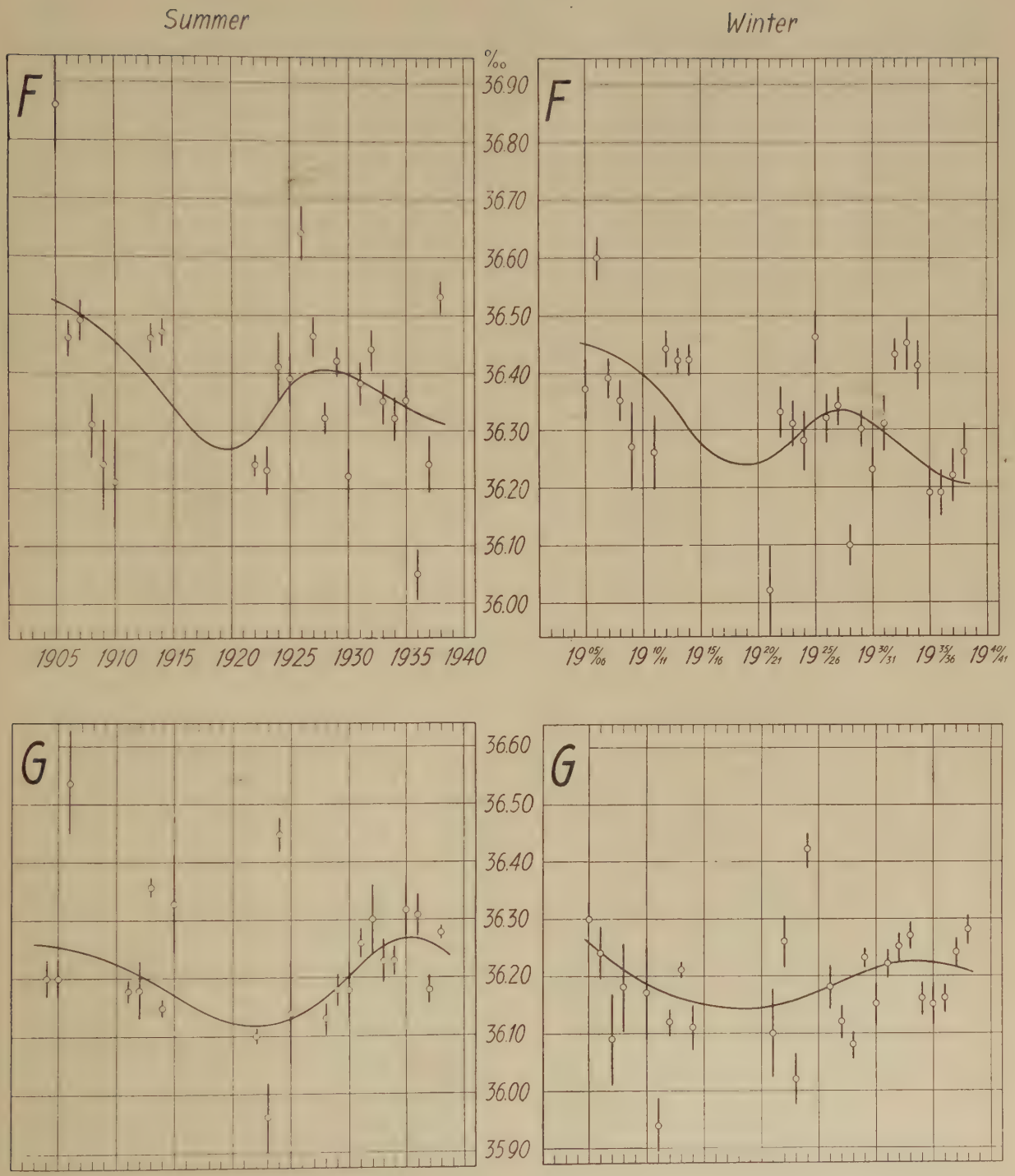


Fig. 8 F, G. Variation of surface salinity from year to year in the areas F and G (see Fig. 7). The standard error of the mean represented by a point is given by half the length of the vertical line through the point.

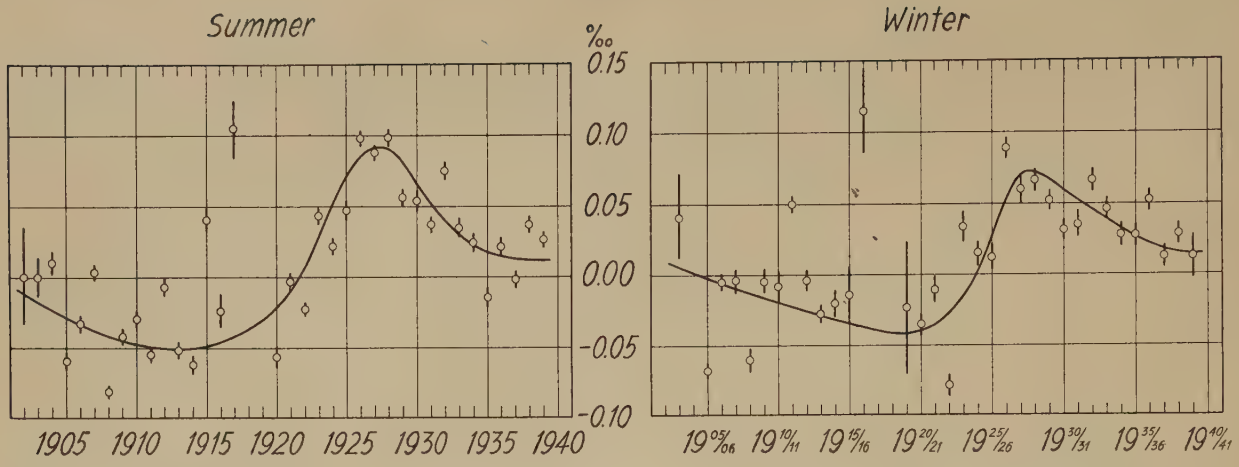


Fig. 9. Anomalies of the surface salinity for the areas A, B, C, D, and E (see Fig. 7) in the summer (May—October) and for the areas A, B, D, and E in the winter (November—April). The standard error of the value represented by a point is given by half the length of the vertical line through the point.

be explained by the scarcity of the material in the years 1915—1920. Far more pronounced is the maximum of the salinity occurring about 1928, from which year the salinity is continuously decreasing. The spreading of the plotted points around the curves is of the same order of size for the areas A, B, C, and E, but extraordinarily great for area D in accordance with the fact that the standard error of the salinity means also is extraordinarily great for this area. The special conditions for the area D are probably due to the influence, even so far east, of the Labrador current. This view is strengthened by the fact that the seasonal variation of the salinity, as mentioned below, is extraordinarily great for this region of the sea.

For the area F — off the Iberian peninsula — it has already been mentioned in connexion with Figs. 5 and 6 that the salinity in 1919—1939 was lower than in 1902—1917. In accordance with this fact the curves for the area F in Fig. 8 are situated lower for the period 1919—1939 than for the period 1902—1917. Excepting this irregularity the run af the curves for the area F is similar to that of the curves for the areas A, B, C, D, and E. For the area G — near the Azores — the variation of the salinity is not the same as for the areas already mentioned. Especially noticeable is the fact that the maximum occurs as late as about 1935.

Table 3.

Area	Summer			Winter		
	σ_1	σ_2	$\frac{\sigma_1^2}{\sigma_2^2}$	σ_1	σ_2	$\frac{\sigma_1^2}{\sigma_2^2}$
A	4·6	2·5	3·4	5·0	2·9	3·0
B	6·7	4·6	2·1	5·8	5·3	1·2
C	8·1	5·3	2·3	—	—	—
D	13·3	10·1	1·7	11·0	9·1	1·5
E	8·9	4·7	3·6	10·7	6·7	2·6
F	12·3	11·2	1·2	11·3	10·7	1·1
G	9·4	8·6	1·2	7·8	7·8	1·0

Having seen that the curves for the areas A, B, C, D, and E, generally speaking, are alike, it seems reasonable to try the construction of general curves for summer and winter respectively but valid for all the said areas. It may thereby be expected that some accidental irregularities will disappear. The material from the summer and from the winter was treated in the same way, but independently of one another. For each area the general mean for all the years was subtracted from the mean salinity for each year. For each year the differences valid for the different areas were averaged with due respect to their weights, as indicated by the reciprocal values of the squared standard errors. The mean values of the differences are plotted in Fig. 9. On the basis of the plotted points the general curves were drawn on estimate. The standard errors of the plotted mean values of the differences are represented in the figure by half the length of the vertical lines through the points.

A consideration of the curves in Fig. 9 shows that the salinity variation under discussion must be a reality. The spreading of the plotted mean values of the salinity around the curves in Fig. 9 is considerably less than in Fig. 8 and in about 20 % of the cases only the plotted means deviate more than three times their standard error from the curves, whereas in about 35 % of the cases the deviation is less than the standard error. Especially for the period 1919—1939 the curves fit very well to the plotted mean values.

It is natural to try if the variation of the surface salinity found in the Atlantic may be traced

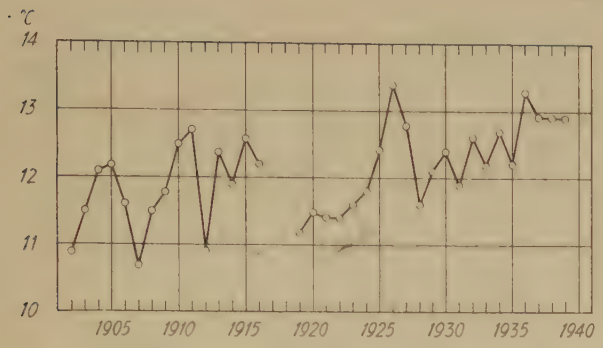


Fig. 10. The surface temperature in August during the years 1902—1939 in the area 59°—61° N., 3°—7° W.

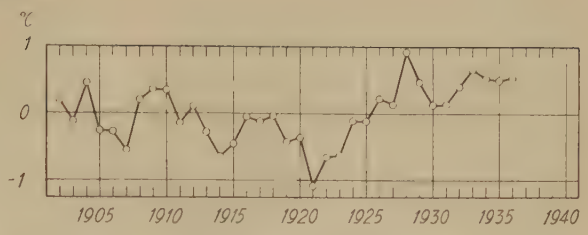


Fig. 11. Deviation of the surface temperature at Selvogsbanki (63°—64° N., 20°—23° W.) in the years 1902—1936 from the mean temperature 1895—1934 after Thomsen (1937).

also in the adjacent waters especially in the North Sea and the English Channel. In these waters, however, the variation of the surface salinity is subject to other predominating factors than in the Atlantic. In fact Jacobsen (1934) and Lumby (1935) have found a minimum of the surface salinity in the North Sea and the English Channel in about 1912 and a maximum in about 1922. The occurrence of these minimum and maximum values is by Jacobsen ascribed to the influence of the variation in the tidal forces.

It has been mentioned already that variations in surface salinity and surface temperature have occurred somewhat parallel. No general investigation of the variation of the surface temperature will be made in this paper; as an example only the mean temperatures of August for the area 59°—61° N., 3°—7° W., are recorded year by year in Fig. 10, compiled from the Danish Nautical-Meteorological Annals. In spite of the irregular distribution of the plotted points, it is evident that an increase of the temperature has taken place from 1902—1917 to 1919—1939. In this connexion reference should be made to the investigations by Thomsen (1937) of anomalies in the temperature of the surface water at Selvogsbanki (63°—64° N., 20°—23° W.). Deviations from the mean temperature, based on observations from 1895—1934, are given by Thomsen and are here plotted in Fig. 11. Generally speaking the variation of the temperature agrees with the variation of the salinity shown in Fig. 9.

In the above the reality of systematical variations of the salinity and the temperature at the surface has been proved. As to the causes of the variations it is hardly possible, however, to arrive at any decision for the present. In the following some possibilities are considered.

In the first place a geographical displacement of the water masses could be submitted as a cause of the variations. As the phenomenon, however, is to be observed over extensive areas, it may be more reasonable to search for causes in the variations of evaporation and precipitation. To get any direct proof of relations of that kind is not possible, as no regular observations of evaporation and precipitation are made in the open sea. It may be possible, however, to ascertain a co-variation of salinity and temperature with some other phenomena depending on evaporation and precipitation.

Supposing the higher salinity within the period 1919—1939 to be due to an increase of the difference (evaporation — precipitation) it would be reasonable to expect greater quantities of vapour being transported across the coasts during that period, thereby causing an increase in the precipitation on land and a stronger outflow of fresh water from the rivers. Thus an increase in the surface salinity of the sea should be followed by an increase of the outflow from the rivers. The records of quantities of water in the rivers Weser and Elbe (Goedecke 1938)[1]) prove the existence of a distinct maximum in outflow in about 1926 in fairly good accordance with the occurrence of the maximum in the surface salinity in the areas A, B, C, D, and E in about 1928 (see Fig. 9).

Accepting the explanation that the variations in the salinity from year to year are mainly due to variations in the difference between evaporation and precipitation a still more pronounced *seasonal* variation in the salinity should be expected. To investigate this question, the Atlantic north of the equator has been divided into areas as shown in Figs. 13 and 14. For each of these areas monthly means were computed from the duly weighted monthly means recorded by Böhnecke (1936) for each 1°-square. The material of Böhnecke practically includes all existing observations — also the older ones — from the part of the Atlantic in question. Some very few mean values recorded by Böhnecke deviated to such a degree from the normal that they were considered erroneous and omitted. If these means had been included in the computations it would, however, not have influenced the results to any appreciable degree. The means computed for the different areas were in most cases directly taken as valid for the centre of the area, notwithstanding the fact that the observations were not equally distributed. For the earlier mentioned areas A, B, C, D, E, and F the 1°-square means given by Böhnecke were

[1]) for the years 1923—36.

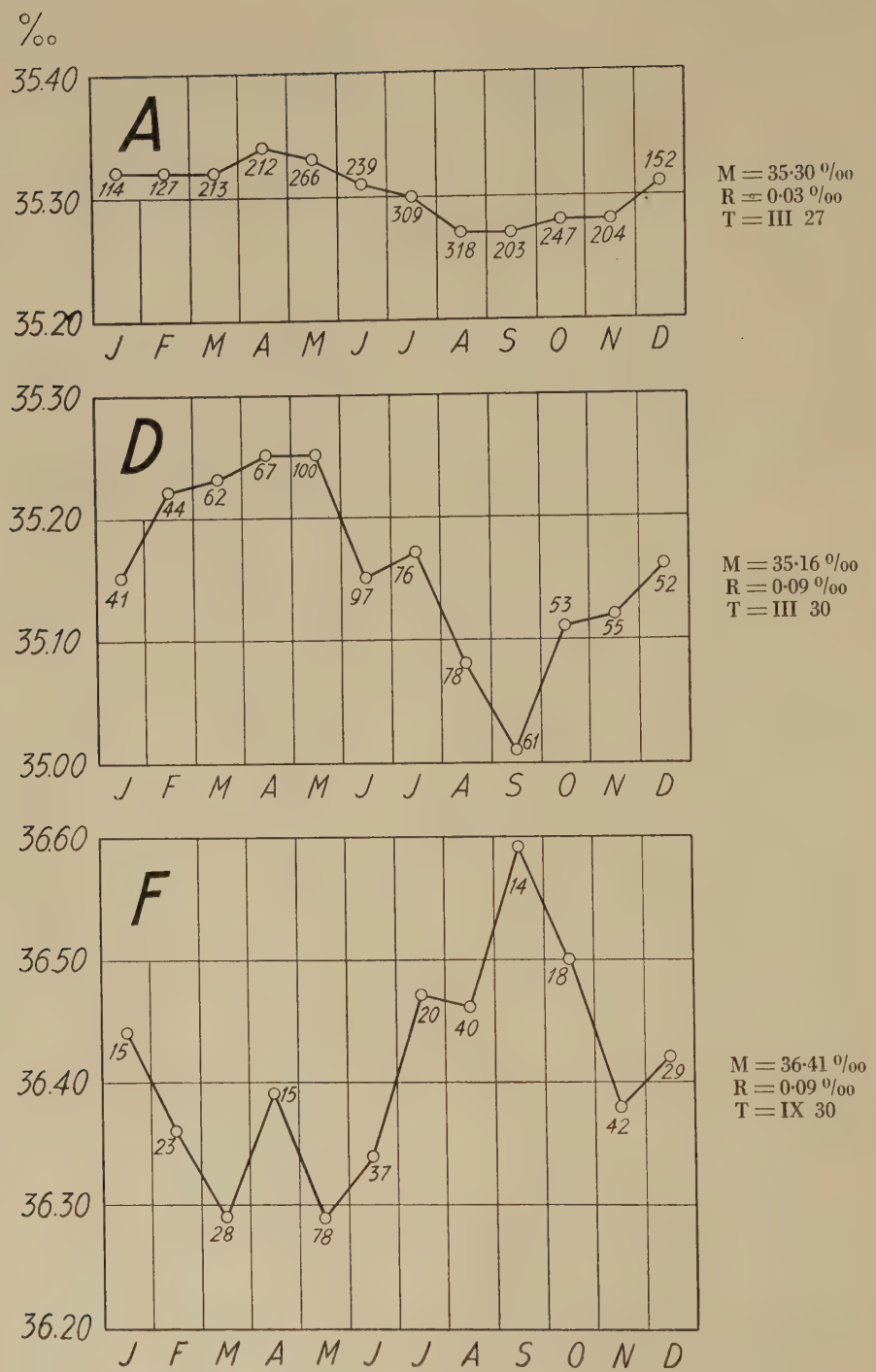


Fig. 12 A, D, F. Seasonal variation of surface salinity in the areas A, D and F (see Fig. 7). M: mean for the year; R: amplitude (i.e. deviation from the mean value); T: date for the occurrence of the maximum. The figures at the points representing the monthly means indicate the number of observations on which the mean in question is based.

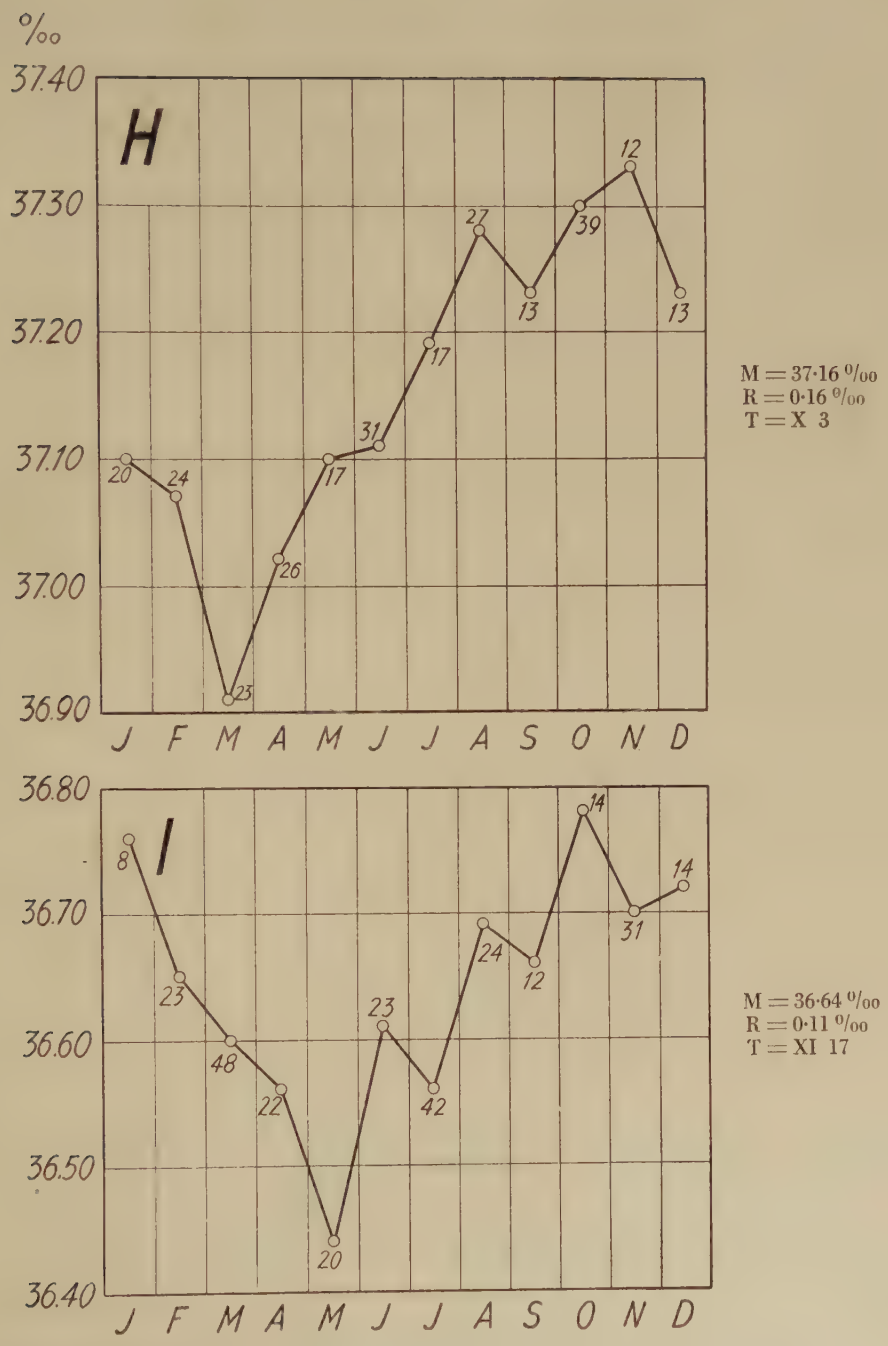


Fig. 12 H, I. Seasonal variation of surface salinity in the areas H and I (see Fig. 7). M: mean for the year; R: amplitude (i. e. deviation from the mean value); T: date for the occurrence of the maximum. The figures at the points representing the monthly means indicate the number of observations on which the mean in question is based.

reduced to the centre of the area by means of the known gradients of the salinity.

The computed monthly means of salinity showed a yearly range that was different for the different areas. Furthermore, the occurrence of the maximum salinity also varied from area to area. As examples of the seasonal variation of the salinity, the monthly means for the areas A, D, F, H, and I (see Fig. 7) are plotted in Fig. 12. At each of the plotted points the number of observations on which the mean value is based, has been recorded. The salinity is seen to vary in rather a regular way from month to month. For some of the other areas, however, the variations would not be as regular as those here recorded.

It is of interest to notice that the seasonal range in the salinity and the previously found variations of the salinity from the period 1902—1917 to the period 1919—1939 are of the same order of size. Thus the question arises if a difference in the distribution of the observations over the year could be of essential influence on the result obtained for the variation of the salinity from year to year. A closer examination has shown, however, that the distribution of the observations over the year was sufficiently alike to exclude most of the said influence and furthermore this influence has to rather a high degree been eliminated, as the summer and winter material were treated separately. On the other hand some irregularities found in the variation of the salinity from year to year may be accounted for by a difference in the distribution of the observations over the year.

As mentioned above the yearly range of the salinity and the occurrence of its maximum vary with the locality. An investigation of this variation was undertaken by means of harmonic analysis of the seasonal variation of the salinity for the different areas. For each area was found the amplitude R, i.e., the deviation from the mean M, and the phase T given as the date for the occurrence of the maximum. For the areas A, D, F, H, and I the values of M, R, and T are recorded in Fig. 12. A general view of the geographical variation of amplitude and phase is given in Figs. 13 and 14 respectively.

The figures and curves in Fig. 13 show that the geographical variation of the amplitude in the main may be characterized as continuous. From very low values in the north-eastern part of the ocean the amplitude increases — generally speaking — moving southwards and reaches its highest value at 5°—10° N. Lat. A secondary maximum is indicated in the neighbourhood of 30° N. Lat. — possibly caused by seasonal displacements of the region where the trade winds are predominating, whereby seasonal variations in the evaporation may arise. Conspicuous are the higher amplitudes for coastal regions — caused by the varying extension of the coastal water according to the season. Very high values are found near the Newfoundland banks, which is naturally explained by seasonal variations in the extension and in the salinity of the Labrador current. The curves representing the different values of the amplitude could ordinarily be constructed without much difficulty. In the most southerly region only, the distribution of the amplitude values is too irregular for the drawing of such curves.

The figures and curves in Fig. 14 show the geographical variation of the phase, i.e., the date of the seasonal salinity maximum. Some few values of the phase found by the harmonic analysis are abnormal, probably owing to the great dispersion of the monthly means. Such values were not reckoned with in drawing the curves. South of 25° N. Lat. such irregularities are found that no curves could be drawn. North of 25° N. Lat. the phase-values vary, generally speaking, in a regular way. In the northern and western parts of the ocean the salinity maximum occurs in the months February—April, but for the southern and eastern parts down to 25° N. Lat. in the months August—November. The transition in the values of the phase between the two regions seems to be rather abrupt. As already mentioned the values of the phase south of 25° N. Lat. seems to be rather accidental, so that the existing differences in the phase at the different localities must be taken with some reservation.

Before finishing this work I should like to express my sincerest gratitude to Dr. J. P. Jacobsen, the Hydrographer of the International Council for the Exploration of the Sea, who has suggested the subject and during the whole period of work on this subject has been most helpful to me. My heartiest thanks are also due to the Hydrographical Consultant of the Council, Professor Martin Knudsen, for the interest with which he has followed my work. I likewise beg to express my gratitude to the Rask-Ørsted Foundation for valuable economic assistance.

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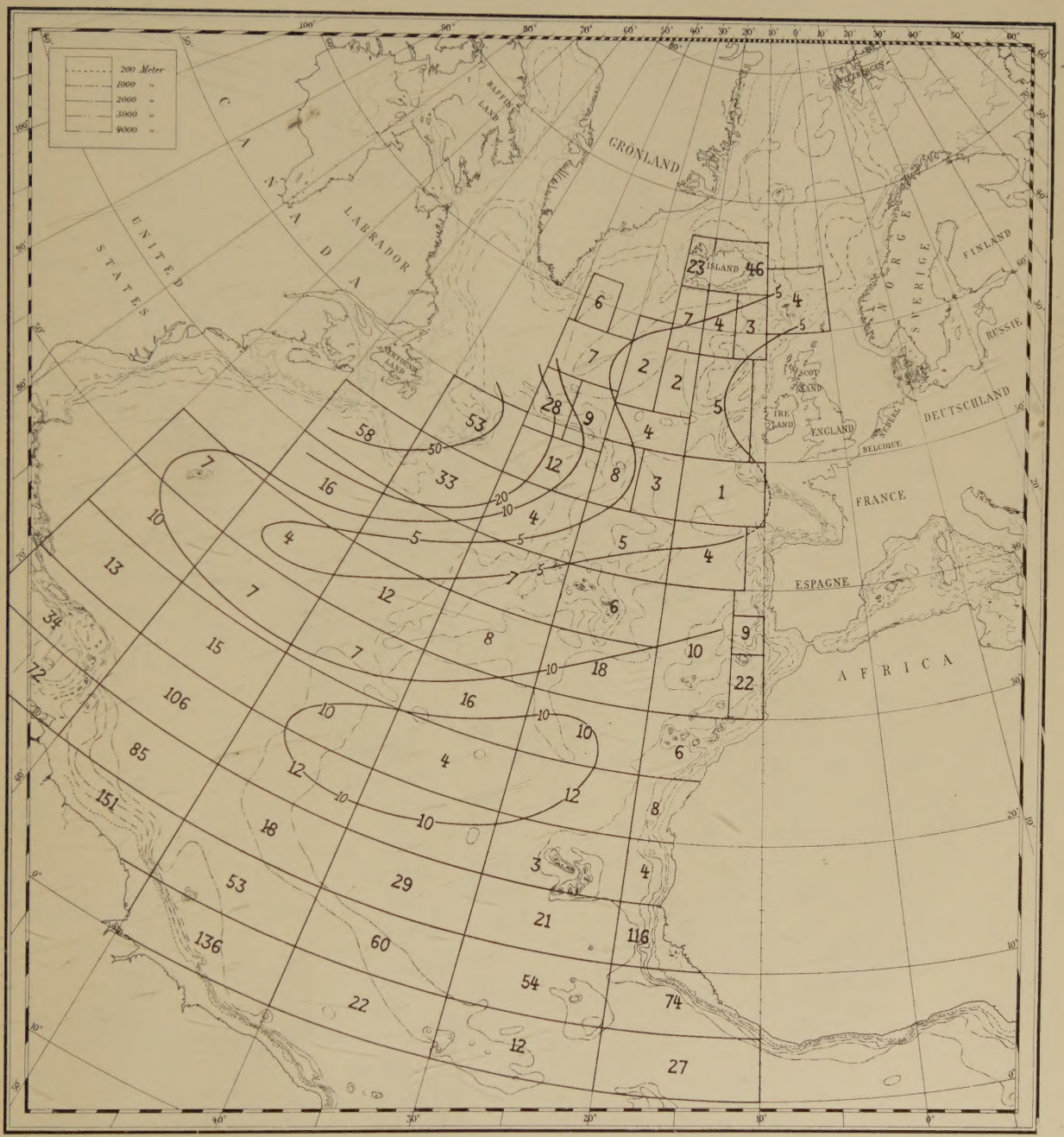

Fig. 13. Amplitude (i.e. deviation from mean) of the seasonal variation of the surface salinity with 0·01 ‰ as unit. The recorded values are found by harmonic analysis. The curves are drawn on the basis of the recorded values with some smoothing.

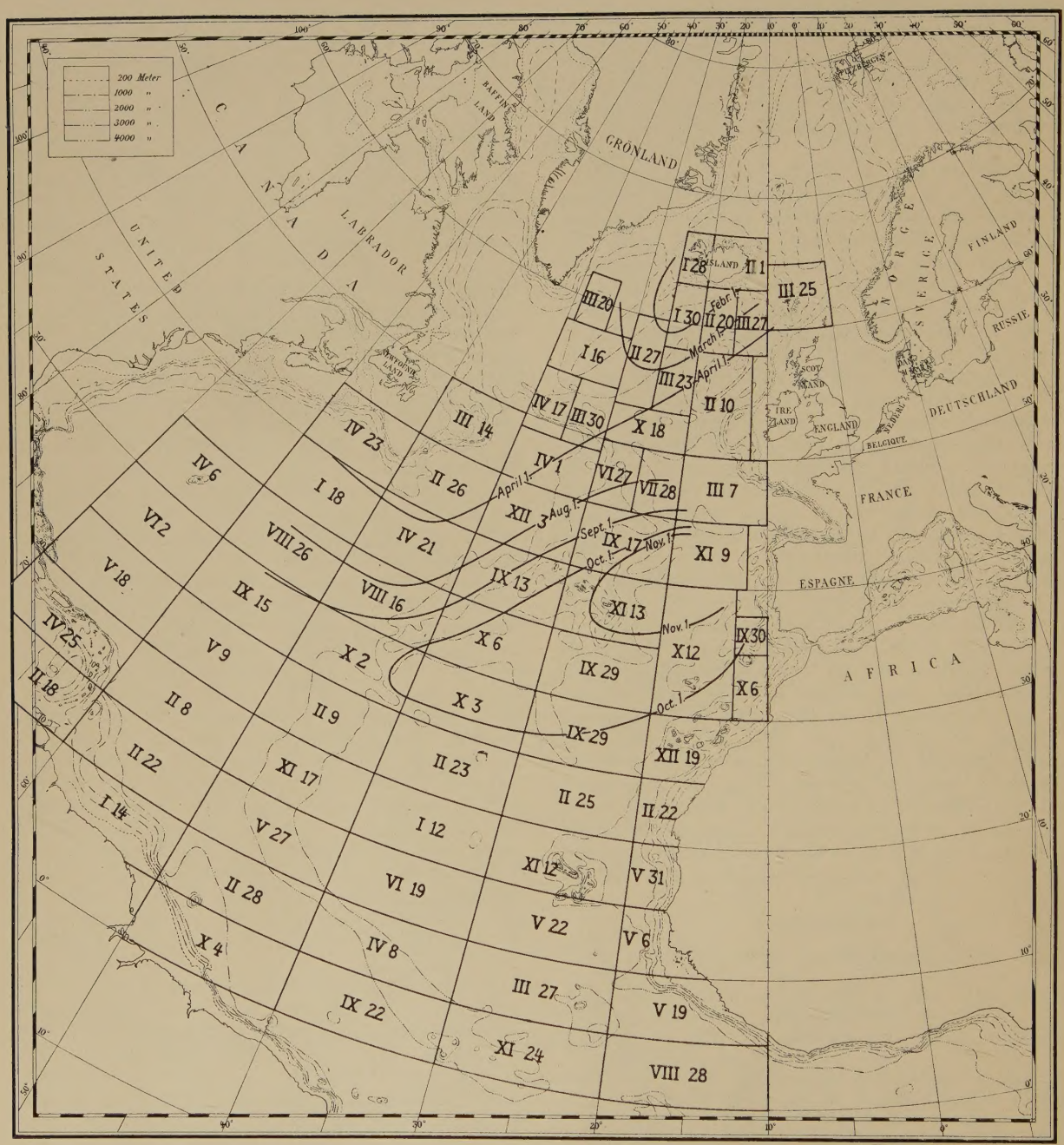

Fig. 14. Date for the occurrence of the seasonal maximum of the surface salinity. The recorded values are found by harmonic analysis. The curves are drawn on the basis of the recorded values with some smoothing.